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REGRESSION MODELING OF TURBINE ENGINE PERFORMANCE.(U)
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REGRESSION MODELING OF TURBINE ENGINE PERFORMANCE

Performance Branch
Turbine Engine Division

May 1980

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Final Report for Period July 1974 - June 1977

AERO-PROPULSION LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
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This effort examines the use of regression modeling to represent turbine engine performance as a function of Mach number, altitude, power setting, design for pressure ratio and design overall pressure ratio. A model, satisfactory for conceptual analysis work, was constructed and evaluated. A significant reduction in propulsion data generation cost was demonstrated (approximately 15 to 1). Details of the approach are presented along with a discussion of the practicality of such a model.

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FOREWORD

This final report describes work done in 1975 through 1978 time period under Project 3066, Task 11, Work Unit 21. All work was carried out within the Performance Branch of the Turbine Engine Division (AFWAL/POTA). J. Ruble and R. McNally were the principle investigators with support from C. Dienstberger and T. Schroyer.

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LIST OF SYMBOLS AND ABBREVIATIONS

A8 - Nozzle Throat Area

A8I - Nozzle Throat Area at Intermediate

A8MAB - Nozzle Throat Area at Max Augmented

CPR - Design Compressor Pressure Ratio

ETABBP - Augmentor Efficiency

ETAB - Main Burner Efficiency

FF - Fuel Flow

FFI - Fuel Flow at Intermediate

FFMAX - Fuel Flow at Max Augmented

FN - Net Thrust (Ideal)

FNI - Net Thrust at Intermediate

FNMAB - Net Thrust at Max Augmented

FPR - Design Fan Pressure Ratio

GFN - Ratio of Thrust Required to Intermediate or Max Augmented Depending on Operating Mode

N1 - Low Spool Physical Speed

N1C - $N1/\sqrt{\theta T2}$

OPR - Design Overall Pressure Ratio

PA - Ambient Pressure

PCN - Percent Corrected Speed (N1)

PCNI - Percent Corrected Speed at Intermediate

PT2 - Total Pressure at Engine Face

PT8 - Nozzle Total Pressure (Throat)

PT8I - Nozzle Total Pressure at Intermediate

PT8MAB - Nozzle Total Pressure at Max Augmented

SFC - Thrust Specific Fuel Consumption

TA - Ambient Temperature

T4 - Turbine Inlet Temperature

TT2 - Total Temperature at Engine Face

TT8 - Nozzle Total Temperature (Throat)

TT8I - Nozzle Total Temperature at Intermediate

V1 - Free Stream Velocity

V2 - Nozzle Exit Velocity (Complete Expansion)

WA - Engine Total Airflow (Physical)

LIST OF SYMBOLS AND ABBREVIATIONS (Concluded)

WAC - WA $\sqrt{\theta T2}$/ST2

θ - Total Temperature/518.67

δ - Total Pressure/14.696

θT2 - Total Temperature at Engine Face/518.67

δT2 - Total Pressure at Engine Face/14.696

γ - Ratio of Specific Heats

SECTION I

BACKGROUND

Over the past several years, the aerospace and propulsion industries have developed highly sophisticated, computerized procedures for the conceptual design and evaluation of both airframes and propulsion systems. More recently these separate computer programs have been combined to form complex weapon system models which may be used to evaluate conceptual weapon system requirements and tradeoffs on airframe and propulsion design characteristics. In their fullest form, these system models provide the user with the capability of exercising a large number of independent airframe, engine and mission(s) characteristics which can, in turn, yield extensive insight about the complex weapon system interactions. However, this insight is available only if the user has some logical and systematic method of evaluating a payoff parameter (TOGW, LCC, etc) as a function of the mission(s) constraints (Takeoff distance, Ps levels, acceleration times, etc) and the independent characteristics. This need for a logical and systematic approach introduces three new elements into the analysis.

The first of these is a constrained optimization procedure. Many currently exist, but they cannot be coupled directly to the engine/airframe/ mission models because they require too many iterations to achieve a solution. To solve this problem, a second element or regression model is constructed through the use of a design of experiments approach to represent the system dependent characteristics as a function of the initially selected independent parameters. The regression model is made up of a set of second order polynominal equations. One equation is developed for each dependent characteristic of interest and is expressed in terms of the independent characteristics. Typically, the regression model will contain one- to two-hundred dependent parameters for a given weapon system concept. The regression model is developed using two- to three-hundred data points which have been selected using a statistical sampling procedure called Latin square. This design of experiments procedure, which is the third element, identifies specific combinations of the independent variables that are to be run through the basic system model to form the required data base for

regression. Briefly, the Latin square procedure insures that a uniform sampling occurs in forming the regression data base. This approach is not totally satisfactory but, in most instances, provides reasonable results. A simplified flow chart of the procedure is depicted in Figure 1.

The great advantage of the regression model is that it can be evaluated very rapidly. Thus, it can be directly coupled to a computerized optimization process to yield estimates of the best airframe configuration or best engine cycle to meet a specific set of mission requirements. Once a best set of characteristics have been identified, the region of interest is further examined using the original system model to preclude inaccuracies that may have been introduced through the use of the regression model. Normally, important parametric sensitivities are also established for use in more detailed refinement work.

The above approach of constructing a weapon system regression model using a Latin square data base has been exercised several times over the past two or three years by McDonnell and Boeing aircraft companies (See References 1 and 2). Much of this work has been sponsored by the APL for the purpose of refining this approach for propulsion concept evaluation and cycle selection. As a result of these and other subsequent efforts, it was found that for propulsion related work 60 to 80 percent of the total cost ($25,000 to $30,000) of applying the procedure was consumed in generating the required propulsion data. In some instances where the propulsion concept was not in a parametric deck form, the costs of generating the required propulsion data in card pack form rose to levels on the order of 40 to 50 thousand dollars.

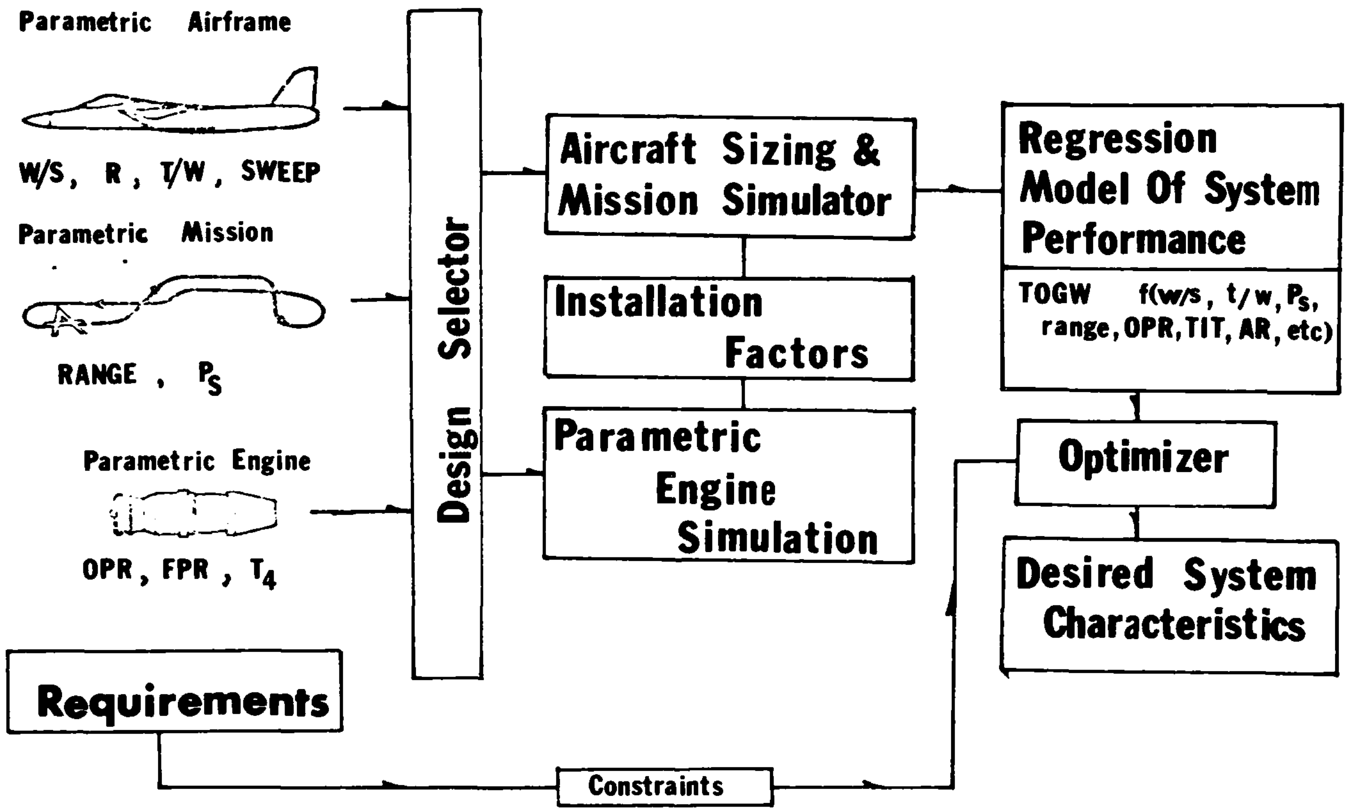


Figure 1. Conceptual System Evaluation Procedure

SECTION II

STUDY OBJECTIVES

As has been pointed out in the previous section, when the procedures outlined in Figure 1 are applied to turbine engine concept evaluation and cycle selection, a large propulsion data base is required. Currently, the cost of generating this propulsion data base can represent 80 percent of the cost of applying the total procedure. Many airframe companies solve this problem by simply reducing the number of propulsion variables considered. However, this often penalizes the propulsion manufacturer in terms of his ability to interpret conceptual study results as they relate to the propulsion system.

Therefore, to overcome the relatively high cost of propulsion data generation and maintain propulsion design visibility, an in-house effort was undertaken to identify the merit and shortcomings of using regression modeling to represent parametric turbine engine performance. The basic objective of this effort was to develop a regression simulation of turbine engine performance that could be used to support system conceptual analysis work at propulsion data cost levels considerably below those presently being incurred. In addition, the practicality of the resulting regression model was assessed in terms of its general application to conceptual weapon system evaluation.

SECTION III

SCOPE

In general, the basic propulsion characteristics that must be considered in the development of a propulsion data base for conceptual analysis work is shown in Table 1. The characteristics identified in Block A may be considered as input to some propulsion data generation procedure. From these input parameters must come the output characteristics shown in Block B. The output information listed basically represents the minimum requirement for the conceptual analysis procedures previously discussed. For any given application, it is necessary to select a specific engine concept, the independent parameters that will represent that concept and the range of each of the independent parameters. This is done in the following paragraphs.

1. SELECTED INDEPENDENT PROPULSION CHARACTERISTICS

In general, the independent characteristics selected to represent the propulsion system would be chosen based on the weapon system concept to be evaluated. For purposes of constructing a propulsion performance regression math model, the independent characteristics were selected to represent a range of realistic applications with some constraint on the number of independent characteristics to be modeled. The selected independent and dependent propulsion characteristics are shown in Table 2. The number of independent parameters, particularly in the cycle characteristics area, has been limited to a level which is projected to yield a reasonable level of success in terms of accurate regression modeling and available resources. The selection of fan pressure ratio and overall pressure ratio is somewhat arbitrary; other cycle characteristics could have been selected such as turbine inlet temperature or bypass ratio.

Inlet recovery will not be explicitly used as an independent parameter. Previous work has indicated that this parameter may be accounted for in an implicit manner, which will be discussed in a later section. Compressor bleed and horsepower extraction have not been considered in this analysis. In most applications, the effects of compressor bleed and horsepower

TABLE 1

PROPULSION DEFINITION FOR CONCEPTUAL

SYSTEM ANALYSIS

BLOCK A	
DESIGN PARAMETERS	EXAMPLES
Engine Concept	-Turbofan -Turbojet -Variable Cycle
Cycle Characteristics	-Fan pressure ratio -Overall Pressure Ratio -Turbine Inlet Temp
Scheduling	-Airflow Matching
Operational Characteristics	-Altitude -Mach Number -Power Setting
Installation Parameters	-Inlet Recovery -Bleed/HP Extraction

BLOCK B	
OUTPUT PARAMETERS	EXAMPLES
Propulsion Performance	-Engine Airflow -Net & Gross Thrust -Fuel Flow
Internal Nozzle Performance	-Total pressure & temperature at nozzle throat -Nozzle Throat Area
Engine Weight & Geometry	-Inlet & Max Diameters -Length -Weight

TABLE 2

PROPULSION REGRESSION MODEL INDEPENDENT/DEPENDENT

CHARACTERISTICS

INDEPENDENT PROPULSION PARAMETERS	
ENGINE CONCEPT	° Mixed Flow Turbofan
DESIGN PARAMETERS	° Fan Pressure Ratio ° Overall Pressure Ratio ° Other Design Parameters
OPERATIONAL PARAMETERS	° Altitude ° Mach Number ° Power Setting
INSTALLATION PARAMETERS	° Inlet Recovery (Implicity Variable) ° Zero Compressor Bleed ° Zero Horsepower Extraction

DEPENDENT PROPULSION CHARACTERISTICS	
OVERALL PERFORMANCE PARAMETERS	° Ideal Net Thrust ° Fuel Flow ° Airflow
NOZZLE THROAT CHARACTERISTICS	° Total Temperature ° Total Pressure ° Physical Throat Area
ENGINE WEIGHT AND GEOMETRY	° Engine Length ° Engine Diameters ° Engine Weight

extraction do not have a significant impact on propulsion concept selection or cycle evaluation.

In examining Table 2, it is seen that the amount of propulsion information needed to support the conceptual analysis procedure shown in Figure 1 is not extensive. However, with the approach of using a regression model for turbine engine performance, the details of internal engine operation are lost. Recovery of this information is left to a more detailed analysis after specific areas of interest are established.

2. RANGE OF SELECTED INDEPENDENT CHARACTERISTICS

Five independent propulsion characteristics have been selected for use in the development of a propulsion regression model based on Table 2. The range selected for each of these variables is shown in Figure 2. The range of design fan and overall pressure ratio shown in addition to the Mach number/altitude envelope, is considered sufficiently general for most transonic/supersonic mission applications for which the selected mixed flow turbofan configuration was formulated. Basically, it is intended that the regression model offer the same flexibility as the original turbofan simulation for the independent variables shown in Table 2. It should also be noted that several independent characteristics relative to the mixed flow turbofan have been fixed, as is shown in Figure 2.

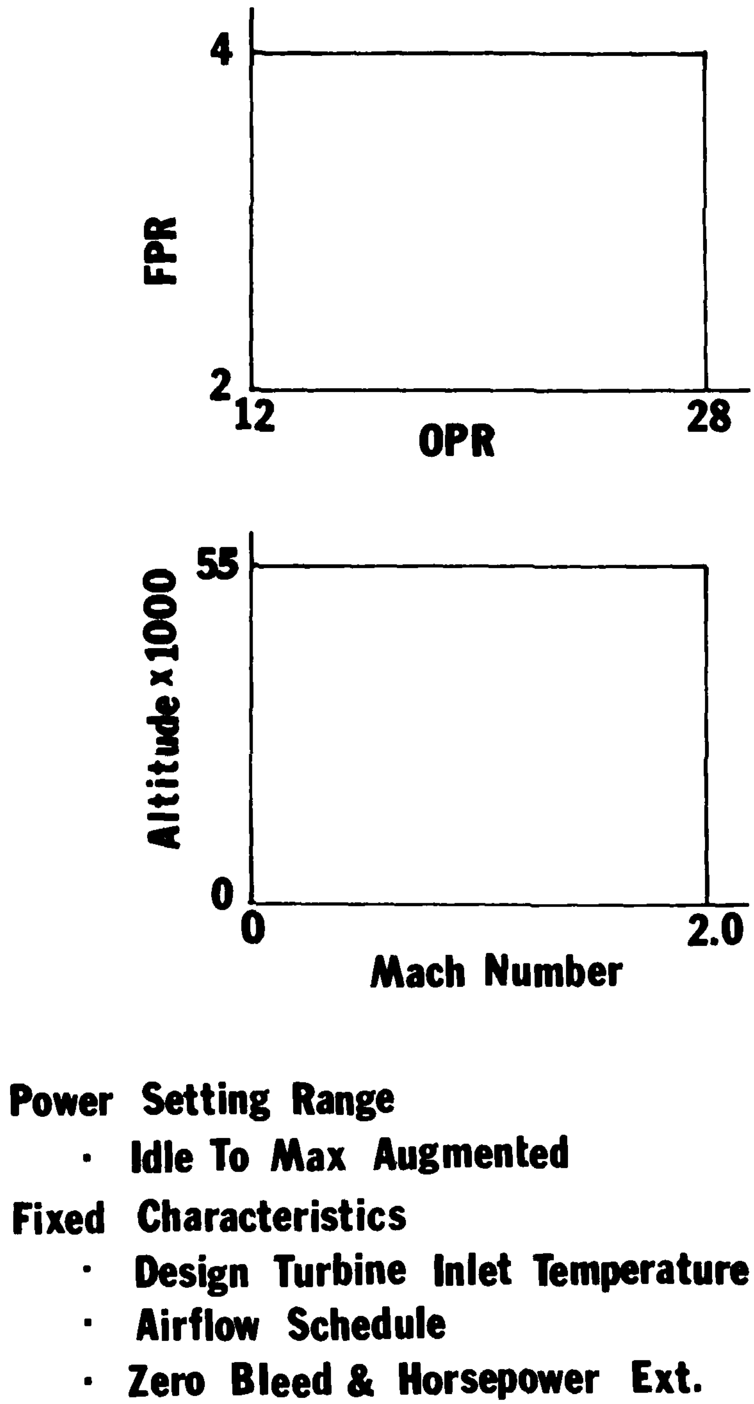


Figure 2. Range of Independent Parameters

SECTION IV

APPROACH

The approach that has been developed is the result of several "trial and error" attempts and approximately one and a half man-years worth of effort. First attempts to develop a regression model of engine performance were carried out by simply using the independent parameters of Table 2 as input for the generation of a propulsion data base using an existing engine computer simulation. The regression model that was developed from this straightforward approach yielded acceptable results in some areas while a total disaster occurred in others. Several alterations have been made since that time including changes in the independent variables, segmenting the data base and higher order polynominals. These and other refinements have led to significant improvements in accuracy at the expense of increased complexity. The final result of these efforts is discussed below.

1. ACCURACY REQUIREMENTS

Until a regression model of propulsion performance is used to support the conceptual analysis procedures previously defined, it is difficult to quantify the accuracy levels required. Certainly, sufficient accuracy is required to permit the user of the conceptual analysis procedure (Figure 1) to arrive at the same conclusions in terms of propulsion concept evaluation or cycle selection as would have been achieved using currently existing procedures.

The absolute accuracy of the regression model for the system conceptual analysis procedure (shown in Figure 1) has not been of paramount importance in comparison to the relative trends of one data point to another. Absolute error levels of five to ten percent are not uncommon, but trend accuracy levels are normally better behaved. In most instances, these levels of error are satisfactory for conceptual analysis and, at the same time, permit a simple, low cost regression model to be generated.

However, these levels of error in trend and absolute value are considered unacceptable for a regression model of propulsion performance. Previous at:empts in industry to construct regression models of propulsion performance have met with only limited success primarily because of accuracy problems. In most of these efforts, errors in excess of one percent (average) were considered excessive. For this reason then, accurate representation of the propulsion data source in magnitude, form and trend were given the highest priority in this effort. This need for accurate representation produced a significant shift away from the procedure developed for weapon system conceptual analysis to a much more detailed and intricate approach.

2. REGRESSION ANALYSIS TOOLS

After the desired independent characteristics have been identified, a data base must be generated, an equation form (normally polynominal in nature) must be selected to represent the data base and a regression procedure to select the equation coefficients must also be chosen. For this analysis, a Latin square data selection procedure was used along with a polynominal equation form and a forward step regression analysis approach. These tools were selected because they had been developed and tested in previous weapon system conceptual analysis efforts (see References 1 & 2) and were readily available for use in this effort.

3. PRELIMINARY CONSIDERATIONS

There are many approaches which may be logically employed in the construction of the regression model. The one discussed here is the result of many trials and a certain amount of ingenuity based on experience. Prior to getting into the details of model construction, several general comments are in order to put this approach in proper prospective.

a. Discussion of Independent Characteristics

In general, the independent operational characteristics of altitude, Mach number and power setting do not correlate well with the dependent propulsion parameters of thrust, airflow and fuel flow. Other independent forms must be developed from these operational inputs for satisfactory accuracy levels to be achieved. Specific examples of the independent characteristics are given in Table 3.

b. Regression Equation Form

The regression equation form used to model the propulsion performance is shown in the most general form below. This polynominal relationship was derived from the forms used in the system conceptual analysis shown in Figure 1. However, in an attempt to improve model accuracy, consideration has been given to many cross-coupling and higher power terms. The complete expansion of this polynominal representation would result in 1056 terms in four variables. In actual practice, three independent characteristics and a polynominal expression of 15 to 20 terms are normally sufficient for satisfactory results. More general representations produced confounding problems which were thought to be attributable to the data selection procedure (Latin square). This problem is discussed in more detail under Data Base Development (Section IV, paragraph 6).

$$U = \sum_{i=0}^{4} \sum_{i=0}^{4} \sum_{k=0}^{4} \sum_{l=0}^{4} (C_{ijkl} \; X^i Y^i Z^k W^l)$$

Where: U is a dependent characteristic, and X, Y, Z, W are independent characteristics and C's are linear coefficients.

Initially, consideration was given to other equation forms which involved transcendental functions such as Fourier Series, log and exponential relationships. But, evaluation of these forms produced a major increase in computer execution time without a corresponding improvement in accuracy. These relationships were therefore eliminated from further consideration.

TABLE 3

BLOCK 1 & 2 REGRESSION MODEL PARAMETERS DRY PERFORMANCE

BLOCK 1		
Dependent Parameters	Selected Independent Parameters	Condition
TT8I/TT2	FPR, AM, OPR	Intermediate
PT8I/PT2	FPR, AM, OPR	
A8I/FPR	FPR, OPR	
FNI/δT2	FPR, AM, FN(Ideal)	
FFI/$\sqrt{\theta T2}\delta$T2	FF(Ideal)	
WA	Constant	Intermediate
PCN	FPR, AM, GFN, CPR	Part Pwr
PT8/PT8I	FPR, AM, PCN	
TT8/TT8I	FPR, AM, PCN, CPR	
A8/A8I	FPR, AM, CPR	
WA/WAI	FPR, GFN, PCN	
ETAB	PCN, OPR, θT2	
FF	FF(Ideal)	
FN	GFN x FNI	Part Pwr

BLOCK 2		
Dependent Parameters	Selected Independent Parameters	Condition
TT8I/TT2	FPR, CPR, θT2	Intermediate
PT8I/PT2	FPR, CPR, θT2	
A8I/FPR	FPR, CPR	
WAI	FPR, CPR, θT2	
PCNI	FPR, θT2	
FNI	FN(Ideal), FPR, PCN, CPR, AM	
FFI	FF(Ideal), FPR, PCN, CPR, AM	Intermediate
PCN	FPR, θT2, GFN	Part Pwr
TT8/TT8I	FPR, CPR, θT2, PCN	
PT8/PT8I	FPR, CPR, θT2, PCN	
A8/A8I	FPR, θT2, PCN	
WA/WAI	FPR, θT2, PCN	
FF	FF(Ideal)	
FN	GFN x FNI	Part Pwr

c. Consideration of Engine Scheduling

Knowledge of the engine scheduling characteristics may be used to significantly simplify the regression performance model. The general scheduling characteristics for the propulsion system used in this analysis are shown in Figure 3. From this figure, it is seen that for the maximum dry and augmented power setting conditions (design level operation) the engine corrected airflow is constant for θT2 levels of 1.0 and less. This act, along with the constant atmospheric temperature in the stratosphere, leads to a subdivision of the Mach number/altitude envelope that simplifies the regression model both in terms of the number of independent characteristics (such as FPR, OPR, MACH, θT2) that must be considered and in the number of terms that appear in the regression expression. Figure 4 depicts the subdivision that was used in this analysis based on the above rationale. Using the subdivisions shown in Figure 4, a dry and augmented performance model was constructed for each of the four blocks shown. The dry and augmented models for Blocks 1 and 2 are independent of one another, i.e., the augmented performance is independent of dry operation in both blocks, and Block 2 dry or augmented performance is not dependent on Block 1. However, both dry and augmented performance in Blocks 3 and 4 are dependent on Blocks 1 and 2, respectively. Rationale for this dependency is given later.

As previously indicated, the operational characteristics of altitude, Mach number and power setting were, in general, not satisfactory as independent characteristics. However, these operational characteristics can be used to obtain PT2, TT2 and GFN, where GFN is defined by the thrust at any condition divided by the maximum thrust at that condition (dry or augmented). Thus, a GFN of one would be either intermediate performance or maximum augmented performance depending on the operating condition. For the most part of the engine is treated as a "black box" with only the engine inlet (TT2, PT2) and throat (PT8, TT8, A8) conditions being considered, see Figure 5. The models for each of the subdivisions were developed in the following manner.

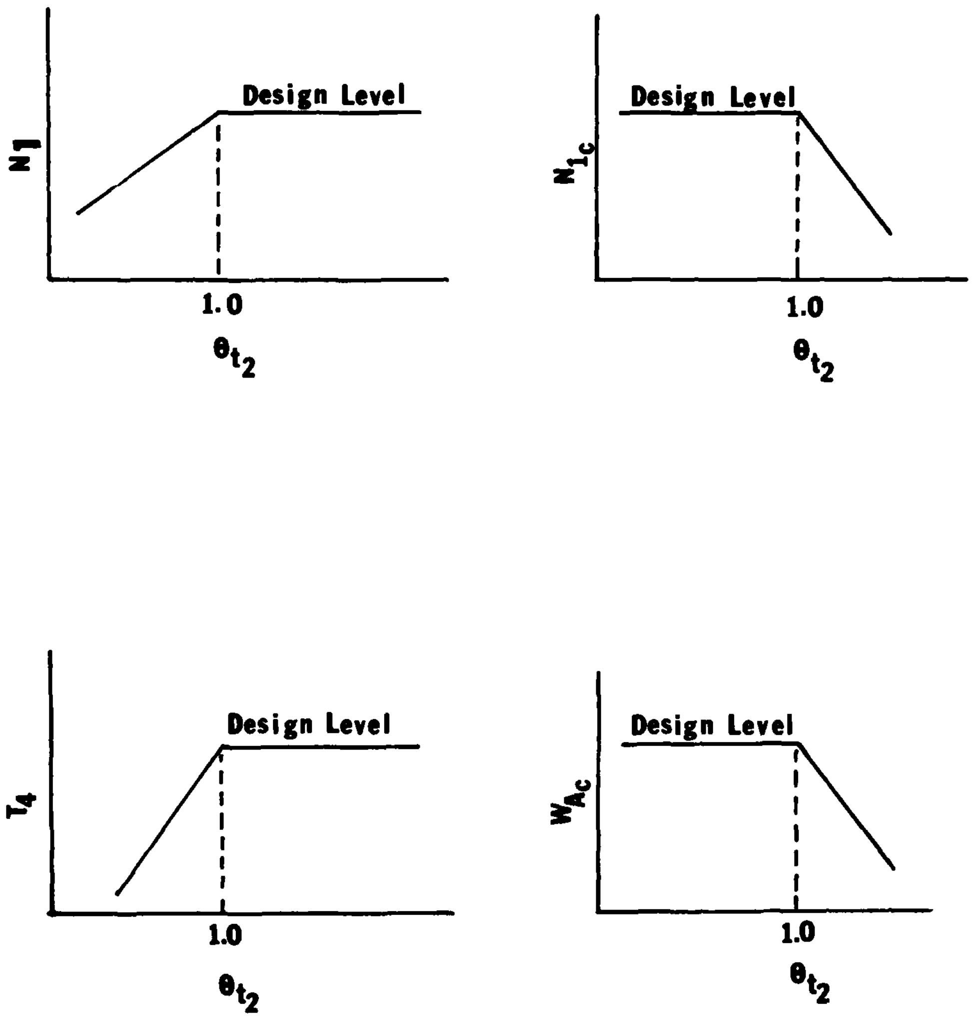


Figure 3. Engine Scheduling Characteristics

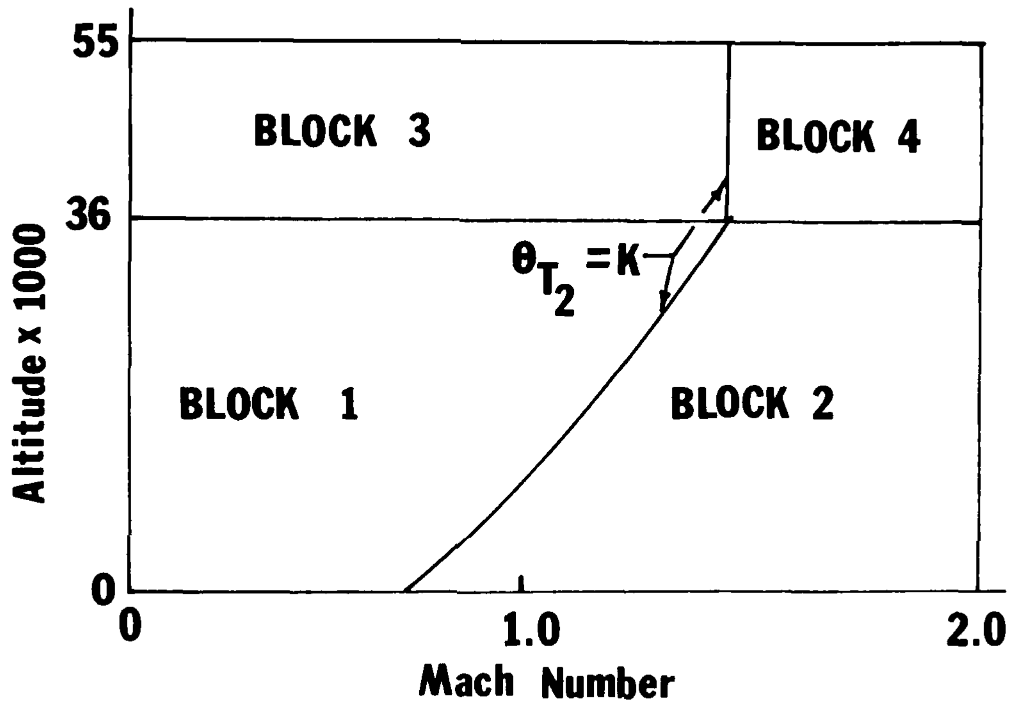
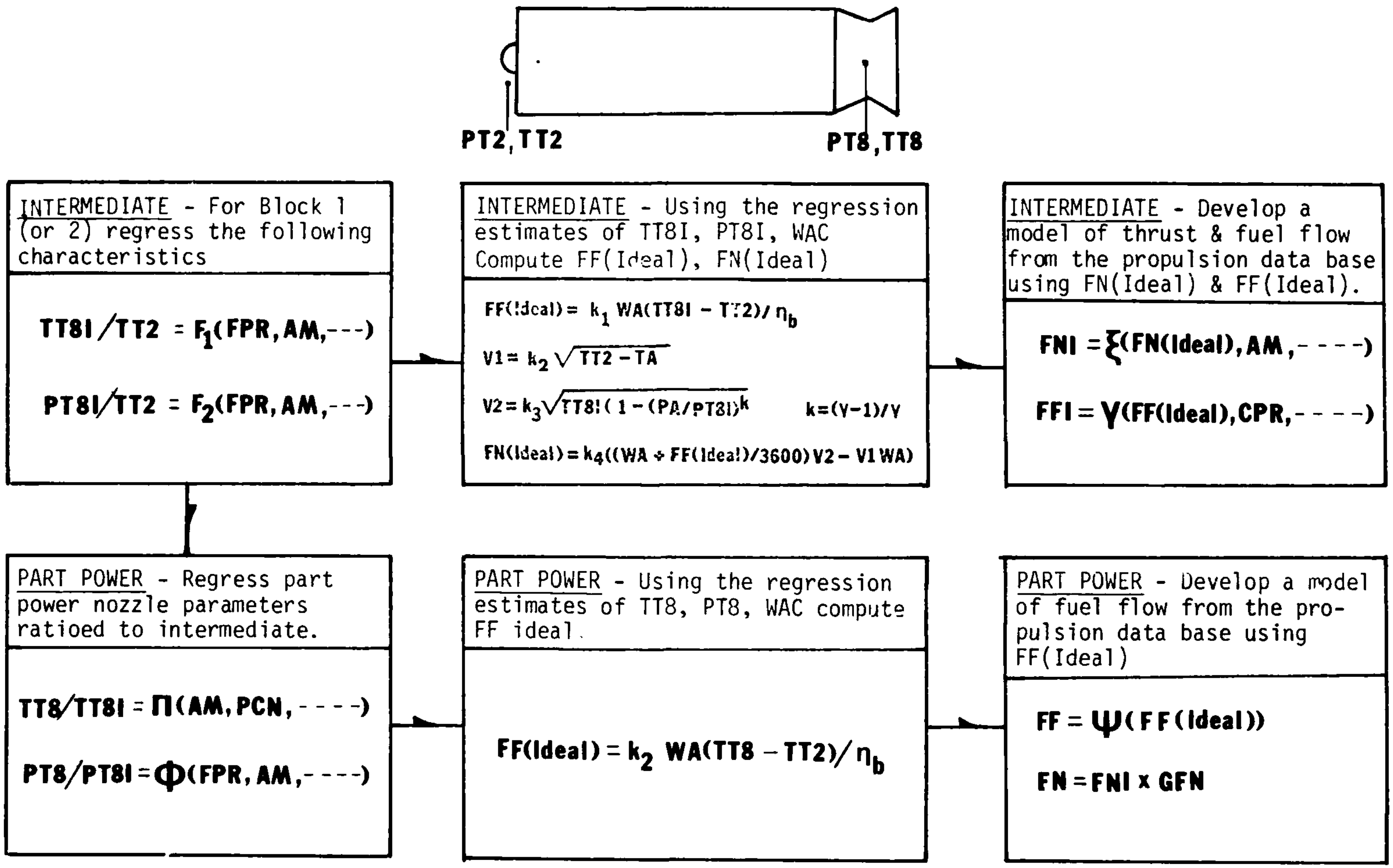


Figure 4. Sub-Model Definition



Notes: 1) TT8I, PT8I for part power ratios must be calculated from the regression model. 2) Augmented performance is formulated in an identical manner.

Figure 5. Regression Model Flowchart

4. PERFORMANCE MODELS FOR BLOCKS 1 AND 2

After much experimentation and evaluation, it was found that consistently good correlations could be obtained between the nozzle throat characteristics (TT8I, PT8I, A8I) and the independent parameters shown in Table 3 for <u>intermediate</u> operating conditions. These regressed throat conditions were then used to obtain an estimate of thrust and fuel flow based on the fundamental relationships shown below.

$$FF(Ideal) = WA(TT8I - TT2)/\eta_b$$

$$V1 = k_2 \sqrt{TT2 - TA}$$

$$V2 = k_3 \sqrt{TT8I\ (1 - PA/PT8I)^k} \qquad k = (\gamma-1)/\gamma$$

$$FN(Ideal) = k_4((WA + FF(Ideal)/3600)V2 - V1\ WA)$$

Note that WA is obtained from WAC, which is constant for intermediate operation in Block 1. Block 2, WAC correlates well with TT2 and the cycle characteristics shown in Table 3.

The values of thrust and fuel flow obtained form the above relationships were then used as independent parameters to obtain a final regressed equation for thrust and fuel flow from the previously existing propulsion model. A flow chart of this procedure is shown in Figure 5. It is very important, in terms of final accuracy, that the regression equations for TT8I, PT8I and WAC be used in the estimates of thrust and fuel flow in the above relationships. This, unfortunately, forces a sequential pattern to be used in the regression model formulation. In other words, the regression equations for PT8I and TT8I must be available before FN(Ideal) and FF(Ideal) can be computed. In turn, the final regression relationships for thrust and fuel flow cannot be obtained until FF(Ideal) and FN(Ideal) are available.

After the regression model for intermediate operation is completed, it is used as a reference for part power operation. The nozzle throat characteristics are ratioed to the corresponding intermediate conditions (TT8/TT8I, PT8/PT8I, A8/A8I) and fitted as a function of the variables shown in Table 3. Note (see Table 3) that percent corrected low spool speed has become an important parameter in this phase of the analysis. Again, the

intermediate performance levels from the regression model for TT8I, PT8I and WAC must be used if best accuracy levels are to be obtained. As before, the part power nozzle throat characteristics (PT8, TT8) are used to calculate an ideal part power fuel flow. A part power thrust is not required since the regression model assumes that a GFN is specified, and part power thrust is simply GFN times the corresponding intermediate thrust level. The augmented performance model is constructed in an identical manner. The independent variables for the augmented model are shown in Table 4.

5. PERFORMANCE MODELS FOR BLOCKS 3 AND 4

The performance models for Blocks 3 and 4 were developed using the fact that the ambient temperature above an altitude of 36,089 ft is constant. This fact greatly simplifies the form of the regression relationships required. In theory, a simple delta ratio of Blocks 1 and 2 performance levels at 36,089 ft should yield the required stratospheric performance numbers. In fact, because of Reynolds number and other effects, this is not the case.

The approach that has been used in developing the performance models for Blocks 3 and 4 is based on the delta ratio approach but with additional terms added as required to provide a more accurate model. A typical set of these regressed relationships is shown in Table 5. Engine performance at an altitude of 36,089 ft is required for input to the Blocks 3 and 4 performance models. This information is obtained from the Block 1 model for Block 3 and the Block 2 model for Block 4.

The augmented models for Blocks 3 and 4 were constructed in a similar manner to their dry counterparts. However, where the dry models required only small corrections to basic delta ratio approach, the augmented models became much more complex. A typical representation is shown in Table 6.

TABLE 4

REGRESSION MODEL PARAMETERS AUGMENTED PERFORMANCE

BLOCK 1		
Dependent Parameters	Selected Independent Parameters	Condition
TT8MAB/TT2	FPR, AM, θT2	Max AB ↓
PT8MAB/PT2	FPR, AM, θT2	
A8MAB/FPR	FPR, CPR, θT2	
FFMAB*	FPR, CPR, θT2	
FNMAB*	FPR, AM, θT2	Max AB
TT8/TT8MAB	FPR, AM, GFN	Part AB ↓
PT8/PT8MAB	FPR, θT2, GFN	
A8/A8MAB	FPR, AM, GFN	
ETAAB	(PT2 * FPR), GFN	
FF	FF(Ideal)/FFMAB, FPR, AM	
FN	FNMAB x GFN	Part AB

BLOCK 2		
Dependent Parameters	Selected Independent Parameters	Condition
TT8MAB/TT2	AM, CPR, θT2	Max AB ↓
PT8MAB/PT2	FPR, CPR, θT2	
A8MAB/FPR	AM, CPR, θT2	
FFMAB*	FPR, CPR, θT2	
FNMAB*	FPR, AM, θT2	Max AB
TT8/TT8MAB	AM, GFN	Part AB ↓
PT8/PT8MAB	FPR, AM, GFN	
A8/A8MAB	FPR, AM, GFN	
ETAAB	GFN	
FF	FF(Ideal)/FFMAB, AM, GFN	
FN	GFN x FNMAB	Part AB

*Not correlated against FF(Ideal), FN(Ideal)

TABLE 5

TYPICAL DRY PERFORMANCE CORRECTION

FACTORS FOR ALTITUDES ABOVE 36,089 FT

PARAMETER ALT > 36,089	GENERAL EQUATION FORM
$WA\sqrt{\theta}/\delta$	$A + B\ (WA\sqrt{\theta}/\delta)_k$
TT8	$A + B\ (TT8)_k + C\ (\delta_{alt} + TT8_k)$
$PT8/\delta$	$A + B\ (PT8/\delta)_k$
Fn/δ	$A + B\ (FN/\delta)_k + C\ (\delta_{alt}/\delta_k)\ (FN)_k (OPR)$
FF/FN	$f\ (SFC_k,\ FPR,\ OPR)$
A8	$A8_k$ (No Correction)

NOTE: Corrections apply to both intermediate and part power performance.

$k = 36,089$ ft

TABLE 6

TYPICAL SET OF AUGMENTED PERFORMANCE CORRECTION FACTORS FOR ALTITUDES ABOVE 36,089 FT

PARAMETERS AT ALTITUDE > 36,089	GENERAL EQUATION FORM
$WA\sqrt{\theta}/\delta$	$A + B\ (WA\sqrt{\theta}/\delta)_k$
TT8	$f\ (TT8_k,\ OPR,\ \delta_{alt})$
$PT8/\delta$	$f\ (\ (PT8/\delta)_k,\ FPR,\ \delta_{alt})$
FN/δ	$f\ (\ (FN/\delta)_k,\ OPR,\ \delta_{alt})$
FF	f (FF(Ideal), FPR)

NOTE: Corrections apply to both max and partial AB operation.

k = 36,089 ft

6. DATA BASE DEVELOPMENT

When several independent variables are considered in an analysis problem it is normally not practical to consider all possible combinations of the independent characteristics. For instance, if five independent variables are considered and each variable has a range of consideration that includes seven levels, 16,807 points must be evaluated to give consideration to all possible combinations. Obviously, in most applications this is not practical. To overcome this problem, statistical procedures have been developed that permit a uniform sampling through the systematic selection of specific combinations of the independent characteristics. A Latin square procedure has been selected for use in this effort. This selection was based primarily on the fact that this procedure was readily available and in a form suitable for direct application.

As previously indicated, five independent variables (OPR, FPR, ALT, Mach No, GFN) have been selected for use in this study; however, only four will be used in developing the Latin square data base. It was felt that an accurate definition of the power hook (GFN variation) could not be obtained from one or two points at each specified condition. Therefore, GFN was omitted from the Latin square data generation and a complete power hook was run at each selected condition. This could be done with little cost increase since the engine simulation model functioned most efficiently in this mode of operation.

In its original form, the Latin square procedure was constructed to support a second order polynominal representation which included only first order coupling terms ($x_i x_j$). This was found to be sufficient for the procedures defined in Figure 1. For this effort, a much higher data density is required to properly identify the higher order (see Paragraph 3.b) cross-product terms. This is basically a "brute force" approach to the problem and was not completely satisfactory, particularily when four independent characteristics were actually used in the regression model construction. (A review of Tables 3 and 4 shows that in many cases three independent characteristics were satisfactory.) Efforts to refine the Latin square procedure to account for higher order interactions were not undertaken during this effort but should be considered in future efforts requiring higher order polynominal representations.

Using the Latin square procedures, two separate data bases were developed, one for altitudes below 36,089 ft (Blocks 1 & 2) and a second for altitudes above this level (Blocks 3 & 4). For altitudes below 36,089 ft, two separate Latin square selections were developed and overlayed. Table 7 contains the specific points selected. Keep in mind that only selected combinations of these independent characteristics were actually evaluated using the engine simulation model. For the first array in Table 7, 231 combinations of altitude, Mach number, FPR and OPR were actually evaluated, with 91 combinations for the second array. Again, at each combination a complete power hook was evaluated from max augmentation to idle. Since, in most cases, each power hook contained eleven points, 2,542 pieces of information (164 unique engine designs) were generated for the Blocks 1 and 2 regression models.

The data were separated for the Blocks 1 and 2 performance models based on the value of $\theta T2$ (Block 1 data, $\theta T2 < 1.0$). It should be noted that since $\theta T2$ is the divider between Blocks 1 and 2, it is more logical to use $\theta T2$ rather than Mach number as one of the four basic independent parameters. Unfortunately, this rather fundamental observation was not made until after the data base had been developed.

The data base for Blocks 3 and 4 was of a relatively low density due to the straightforward delta ratio modeling procedures used in these two blocks. The selected array is shown in Table 8. Ninety-one (91) cases were evaluated for these two blocks with a total of 1,009 data points.

7. DISCONTINUITIES BETWEEN REGRESSION MODELS

In general, discontinuities in engine performance will exist at the common boundary between any two regression models. As can be seen in Figure 6a, this condition exists in both thrust and fuel flow at the Block 1/Block 2 boundary. To overcome this problem, a linear interpolation procedure was used to provide a smooth transition from one block to another. A band of approximately ± 4 percent is placed about the $\theta T2$ boundary in

Figure 4 for Blocks 1 and 2. A linear interpolation is then made for any Mach number/altitude points that fall within the band area. A typical example of the resulting transition is shown in Figure 6b. At the present time, this procedure is applied only to thrust and fuel flow. The transition from Block 1 to Block 3, and Block 2 to Block 4 is well-behaved since a modified delta ratio procedure is applied to data that has been generated from either Blocks 1 or 2 at an altitude of 36,089 ft.

8. RAM RATIO VARIATION

From the performance model description (Section IV, 4 & 5), it is seen that regression model engine performance (PT8, TT8) is either directly or indirectly dependent on PT2 and TT2. Thus, ram recovery variations may be approximated by simply adjusting PT2 to represent the appropriate level of this parameter. The approach has proven very satisfactory. An error analysis for the procedure is presented in the following section.

TABLE 7

LATIN SQUARE SELECTIONS

FOR THE INDEPENDENT PARAMETERS

BLOCKS 1 & 2

ALT	MACH	FPR	OPR	
0	0	2.0	12.0	11 by 11 Latin Square
3608	0.2	2.2	13.6	
7217	0.4	2.4	15.2	
10826	0.6	2.6	16.8	
14435	0.8	2.8	18.4	
18055	1.0	3.0	20.0	
21653	1.2	3.2	21.6	
25262	1.4	3.4	23.2	
28871	1.6	3.6	24.8	
32480	1.8	3.8	26.4	
36089	2.0	4.0	28.0	
0	0	2.00	12.00	7 by 7 Latin Square
6014	0.33	2.33	14.66	
12029	0.66	2.66	17.33	
18044	1.00	3.00	20.00	
24059	1.33	3.33	22.66	
30074	1.66	3.66	25.33	
36089	2.00	4.00	28.00	

TABLE 8

LATIN SQUARE SELECTIONS

FOR THE INDEPENDENT PARAMETERS

BLOCKS 3 & 4

ALT	MACH	FPR	OPR	
36089	0.50	2.00	12.0	7 x 7 Latin Square
39240	0.75	2.33	14.66	
42392	1.00	2.66	17.33	
45544	1.25	3.00	20.00	
48696	1.50	3.33	22.66	
51848	1.75	3.66	25.33	
55000	2.00	4.00	28.00	

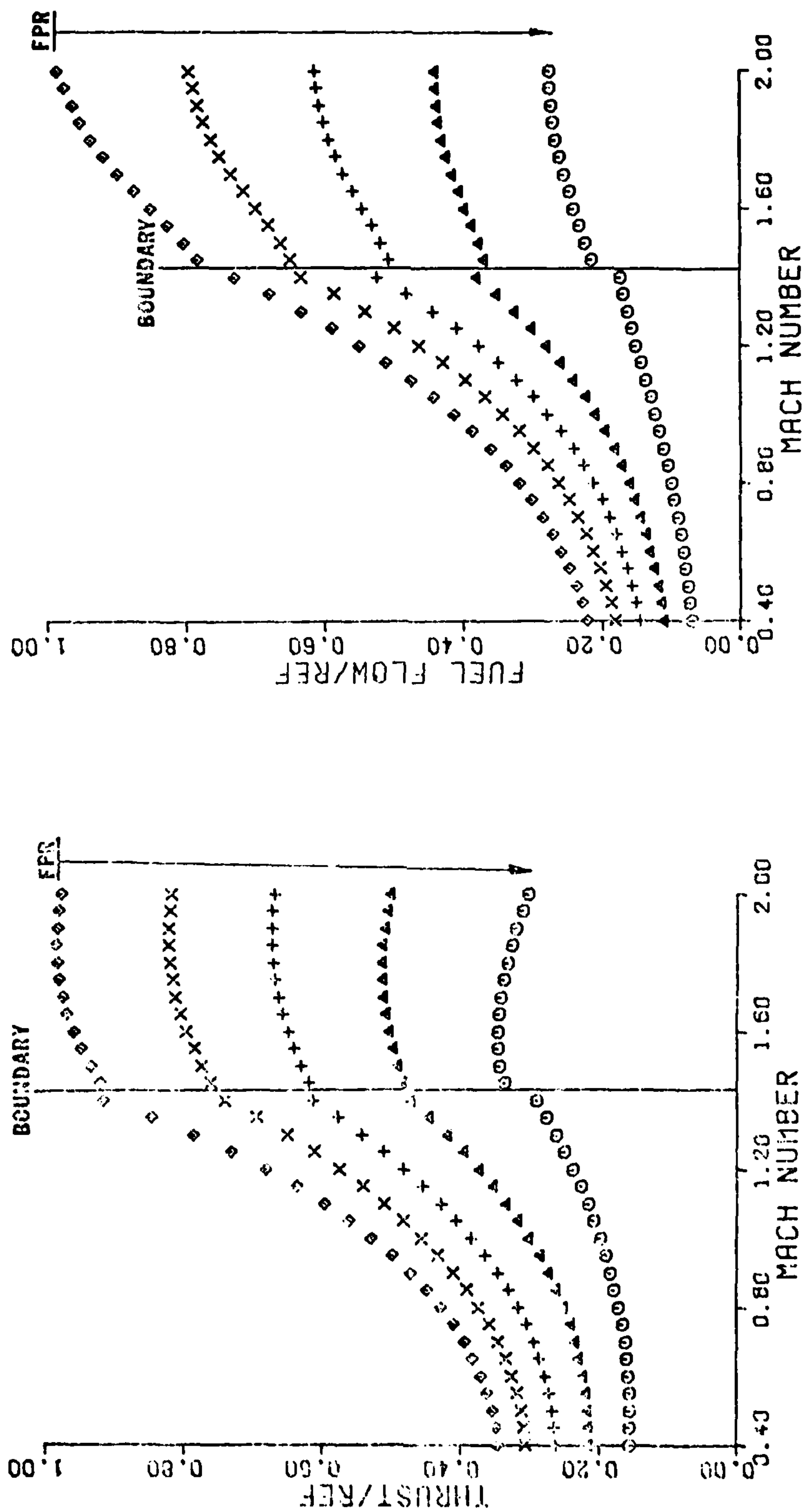


Figure 6a. Regression Model Boundary Discontinuity

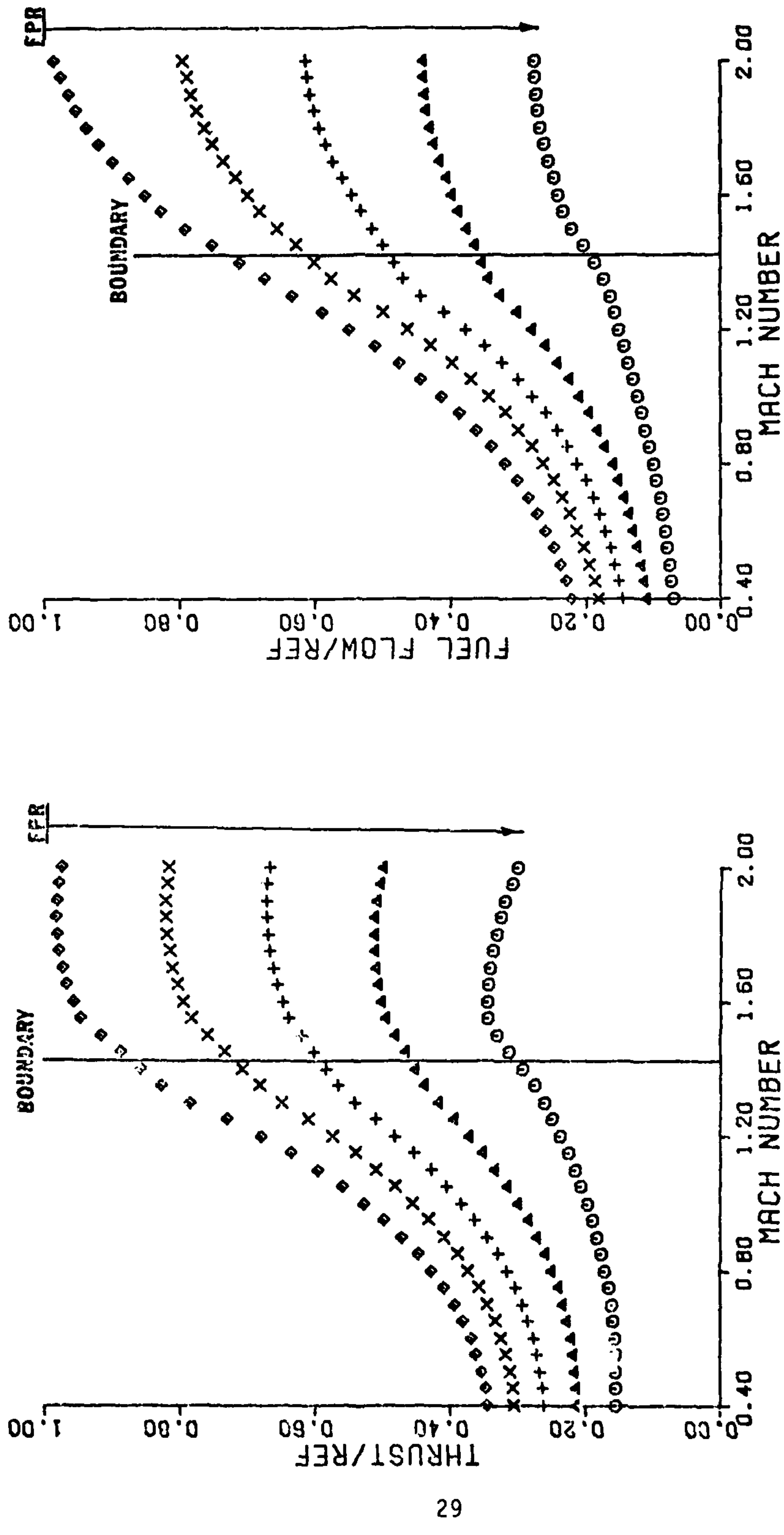


Figure 6b. Result of Discontinuity Correction

SECTION V

MODEL EVALUATION & VALIDATION

Using the procedures outlined in Section IV, a computer model using the regression equations was constructed to permit an evaluation of the regression approach and to allow a cost assessment to be made in comparison to the original engine simulation. The regression model was assembled so that it could function in the same manner as the conventional engine simulation both in terms of input and output for the basic engine parameters. Consideration was also given to the direct coupling of the regression performance model to a Weapon System Assessment Program such as that shown in Figure 1. Through direct coupling, the need for propulsion data tables would be eliminated. The computer program resulting from this work is referred to as Regression Simulation of Turbine Engine Performance Model or RSTEP.

Two types of comparisons are made using this model. The first is a direct one-on-one comparison of the RSTEP output with the original regression data base. The second is an error analysis using a new Latin square data base which was not used in generating the regression equations. A separate error analysis is also presented to show the impact of using non-standard (as opposed to Mil Spec) ram recovery levels.

1. DIRECT COMPARISON

Four separate, direct comparisons are made using the original engine simulation as one data source (symbols) and RSTEP as the other (solid lines). Comparisons were made at the following conditions:

Power Setting	Mach Number	Altitude
Intermediate	Sweep 0.0 to 2.0	0, 36,089, 45,000
Max Augmentation	Sweep 0.0 to 2.0	0, 36,089, 45,000
Dry Part Power	0.0, 0.85, 0.90	0.0, 36,089, 45,000
Partial Augmentation	0.0, 0.9, 1.2, 2.0	0.0, 36,089, 45,000

a. Intermediate Comparison

For the intermediate comparison, Figures 7 through 15, data is presented for three overall pressure ratios (12, 20, 28) and five fan pressure ratios (2.0, 2.5, 3.0, 3.5, 4.0) as a function of Mach number. It should be noted that regression models normally show their poorest behavior at multiple boundaries, (upper or lower range of the independent variables). For this comparison, multiple boundaries occur at fan pressure ratios of 2.0 and 4.0 in combination with overall pressure ratios of 12 and 28 and Mach numbers of 0.0 and 2.0.

At zero altitude, thrust, fuel flow, and airflow, (Figures 7, 8, and 9 repsectively), all show good correlations with the original engine simulation out to Mach numbers of 1.2 to 1.3. A moderate deviation does occur in fuel flow (FPR = 2.0, OPR = 28), but is not of major concern since most aircraft would not operate beyond a Mach number of 1.2 at sea level.

At an altitude of 36,089 ft, a good correlation is observed throughout the Mach number range. A similar observation can be made for the 45,000 ft altitude condition except for fuel flow at FPR = 2.0, OPR = 12 and Mach numbers in excess of 1.5. Again, this is not considered a serious problem due to the nonoptimum characteristics of this cycle combination at high Mach numbers.

b. Max Augmented Comparison

The correlation for max augmented performance (Figures 16 to 20), is good to excellent for all altitudes but one. A highly inaccurate response occurs in fuel flow at the 36,089 condition for FPR = 2.0 and OPR 28.0. This anomaly was investigated and corrections identified; however, the resulting corrections produced accuracy degradations in the remainder of the augmented model and were not incorporated. It can be argued that in most applications, max augmented operation below a 0.50 Mach number at 36,000 ft is a transient operational area and should not impact study results.

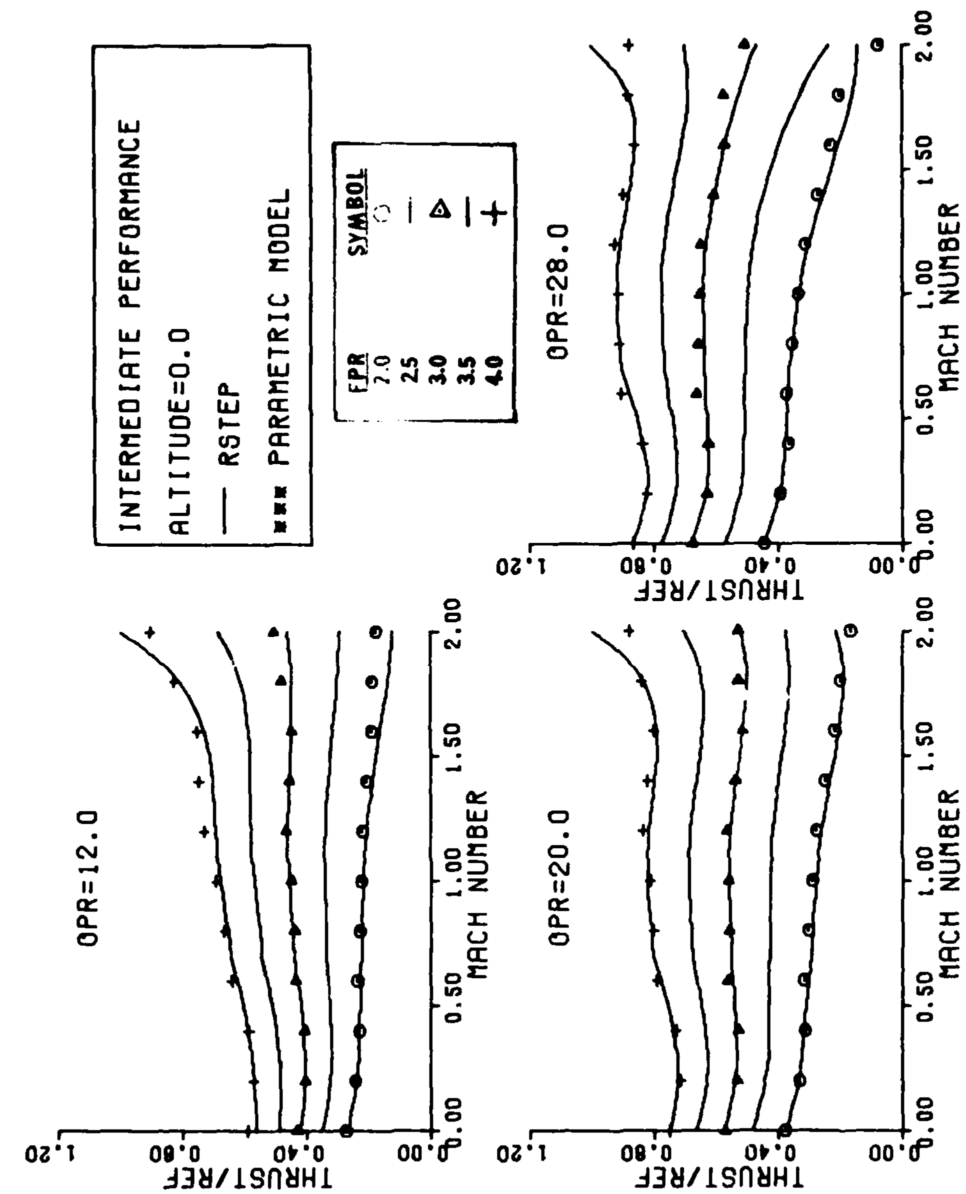


Figure 7. Intermediate Thrust Comparison at Sea Level

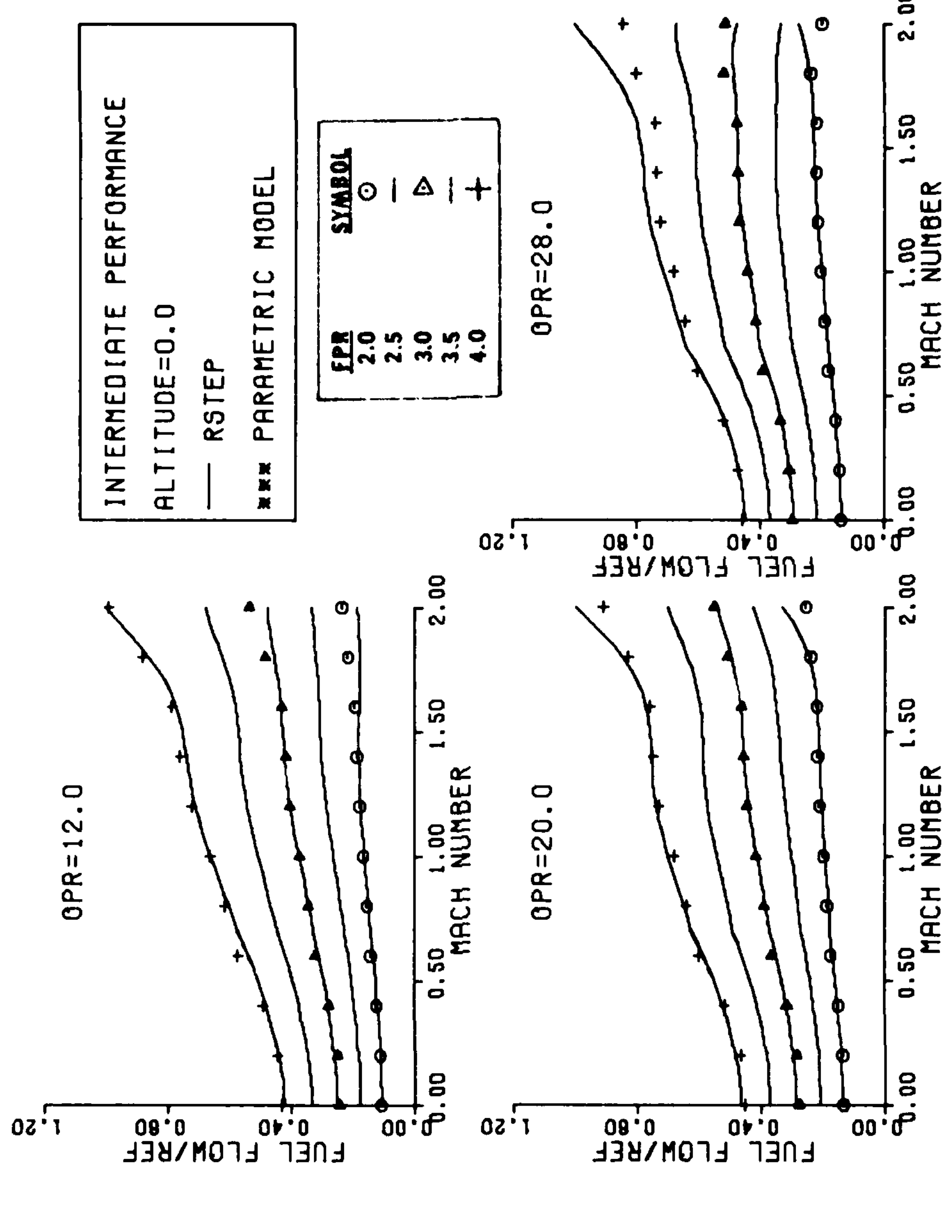


Figure 8. Intermediate Fuel Flow Comparison at Sea Level

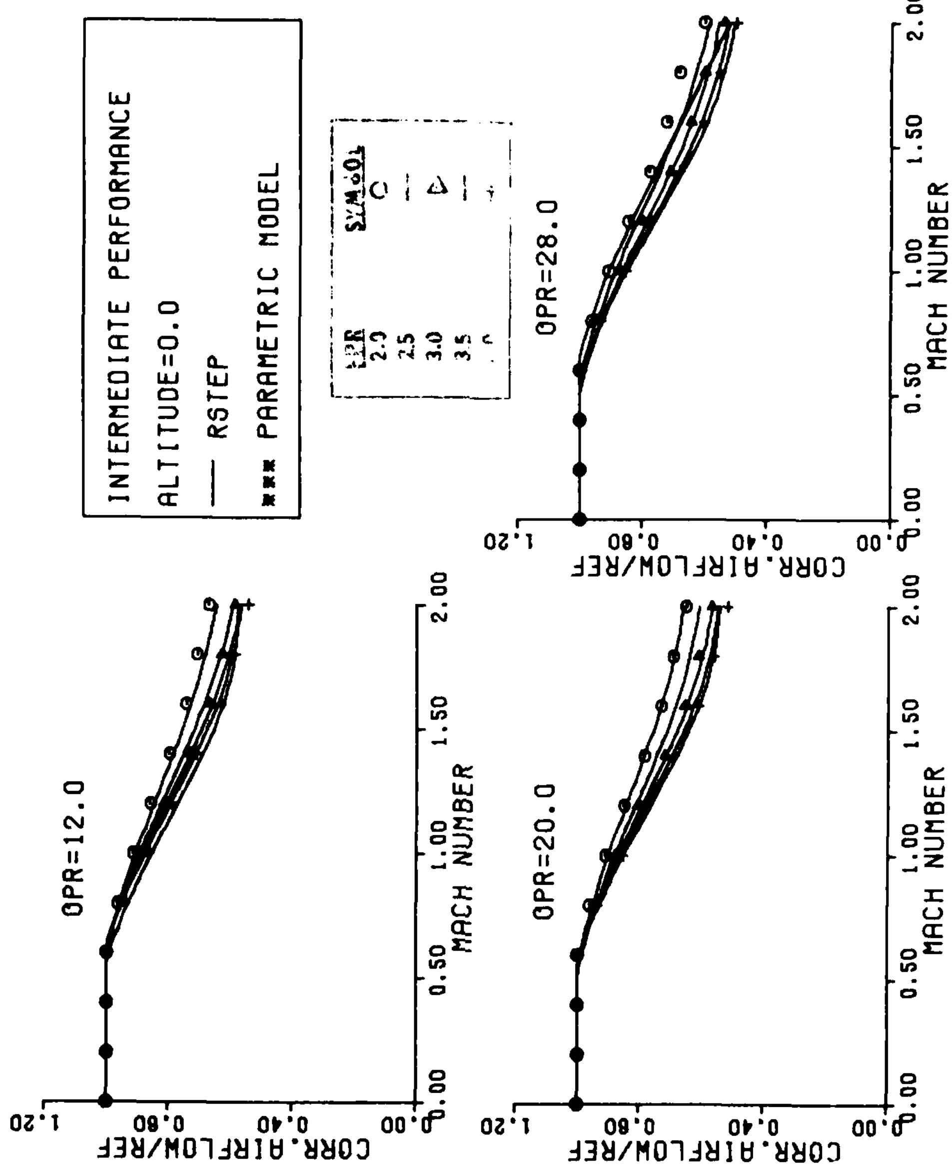


Figure 3. Intermediate Airflow Comparison at Sea Level

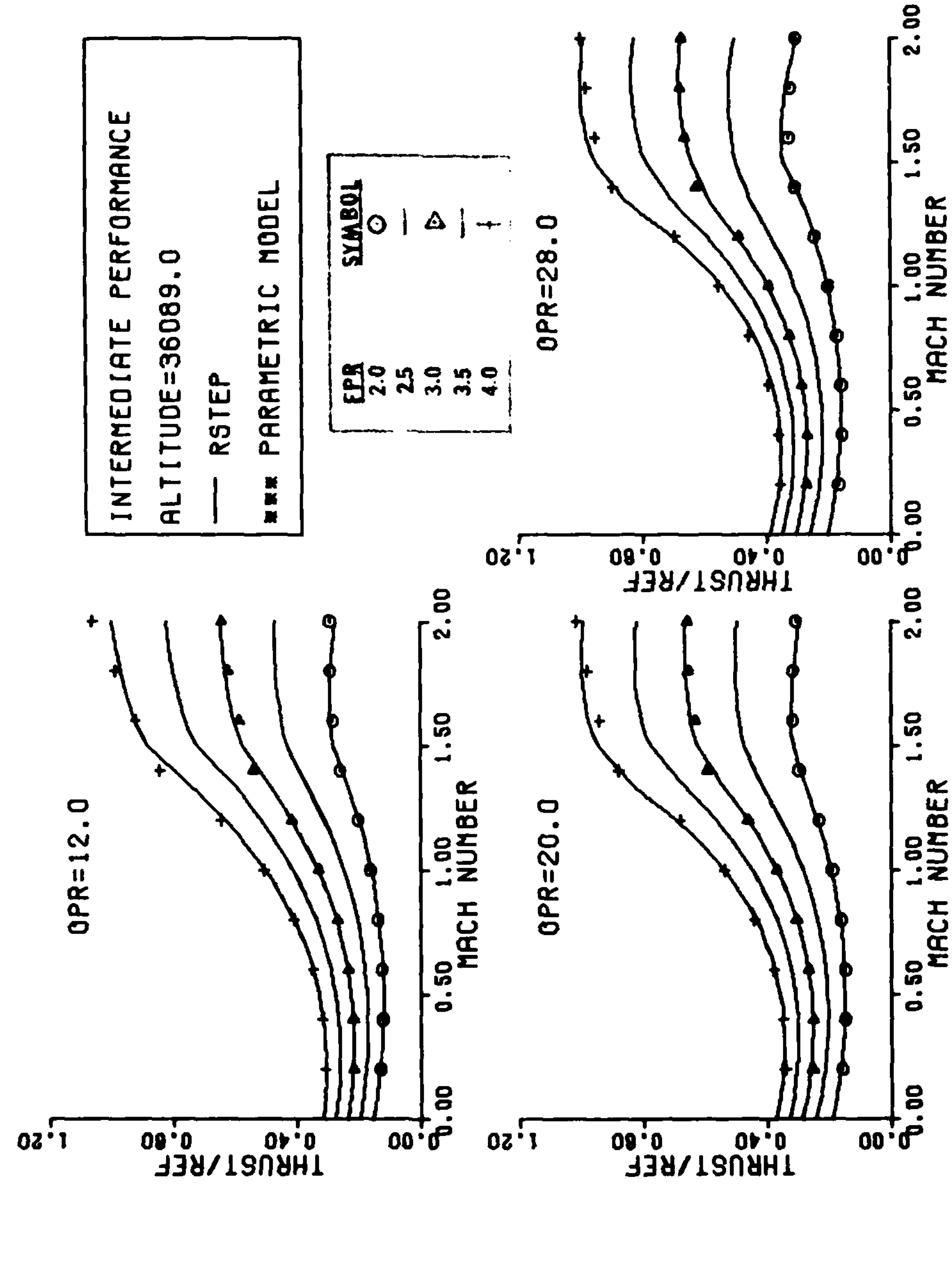


Figure 10. Intermediate Thrust Comparison at 36,089 Feet

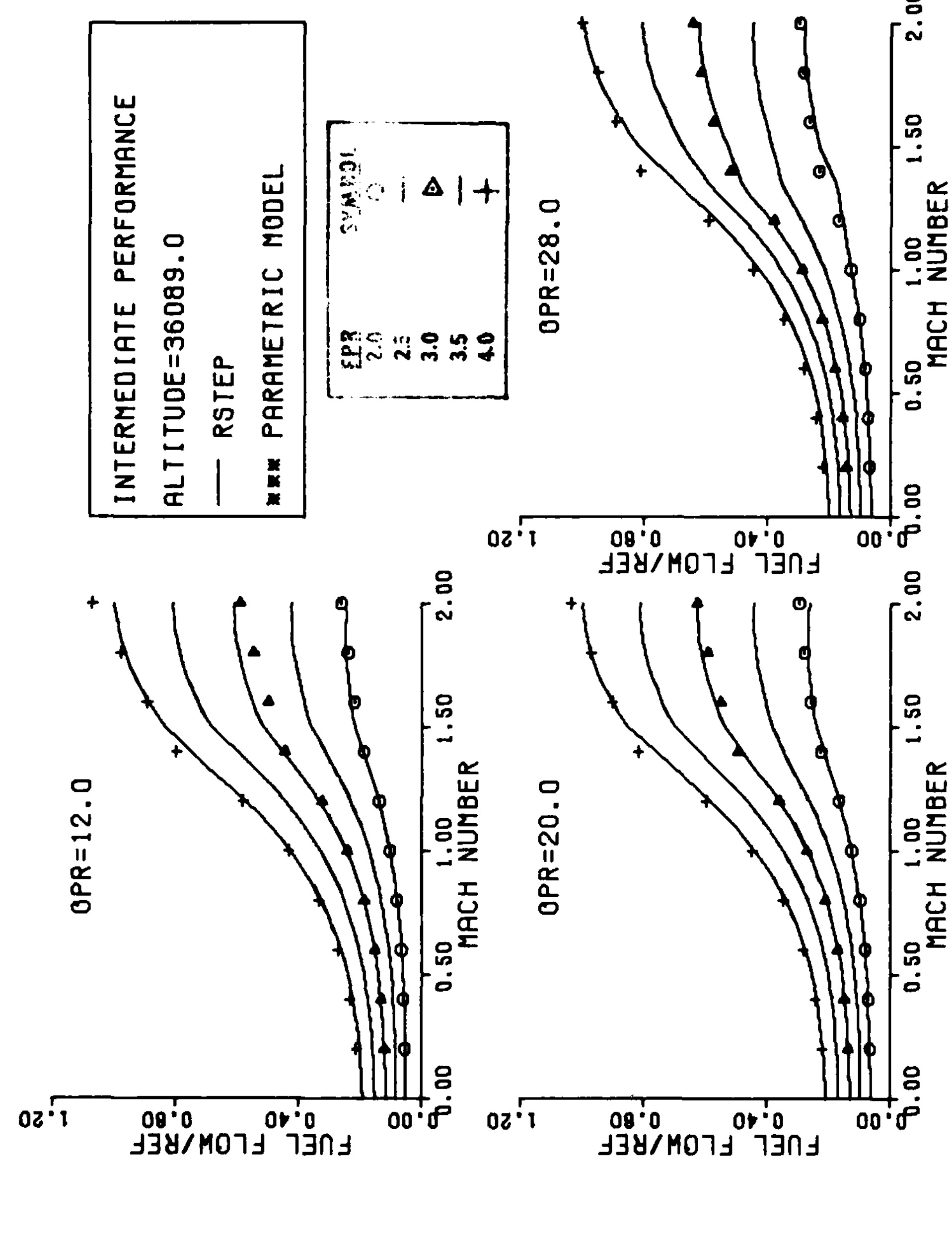


Figure 11. Intermediate Fuel Flow Comparison at 36,089 Feet

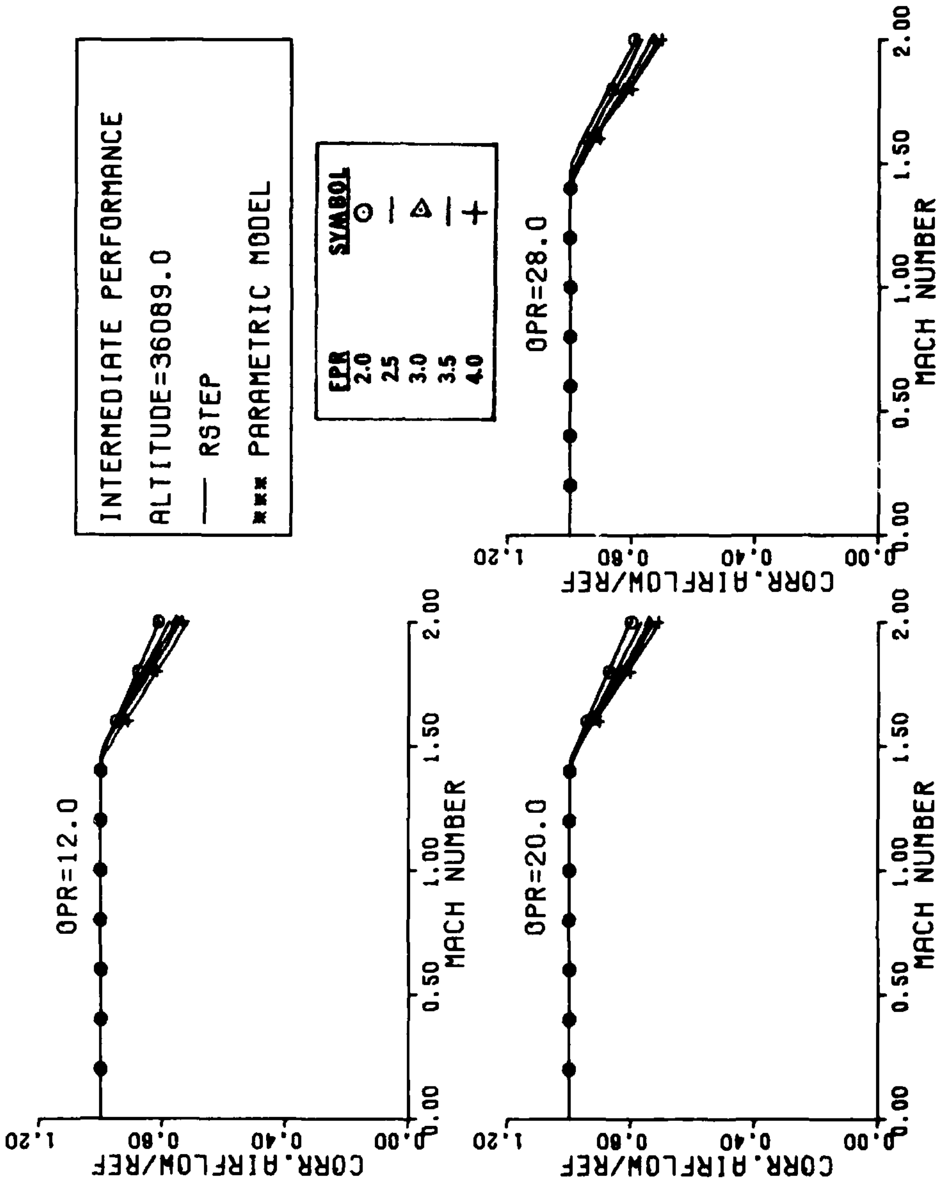


Figure 12. Intermediate Airflow Comparison at 36,089 Feet

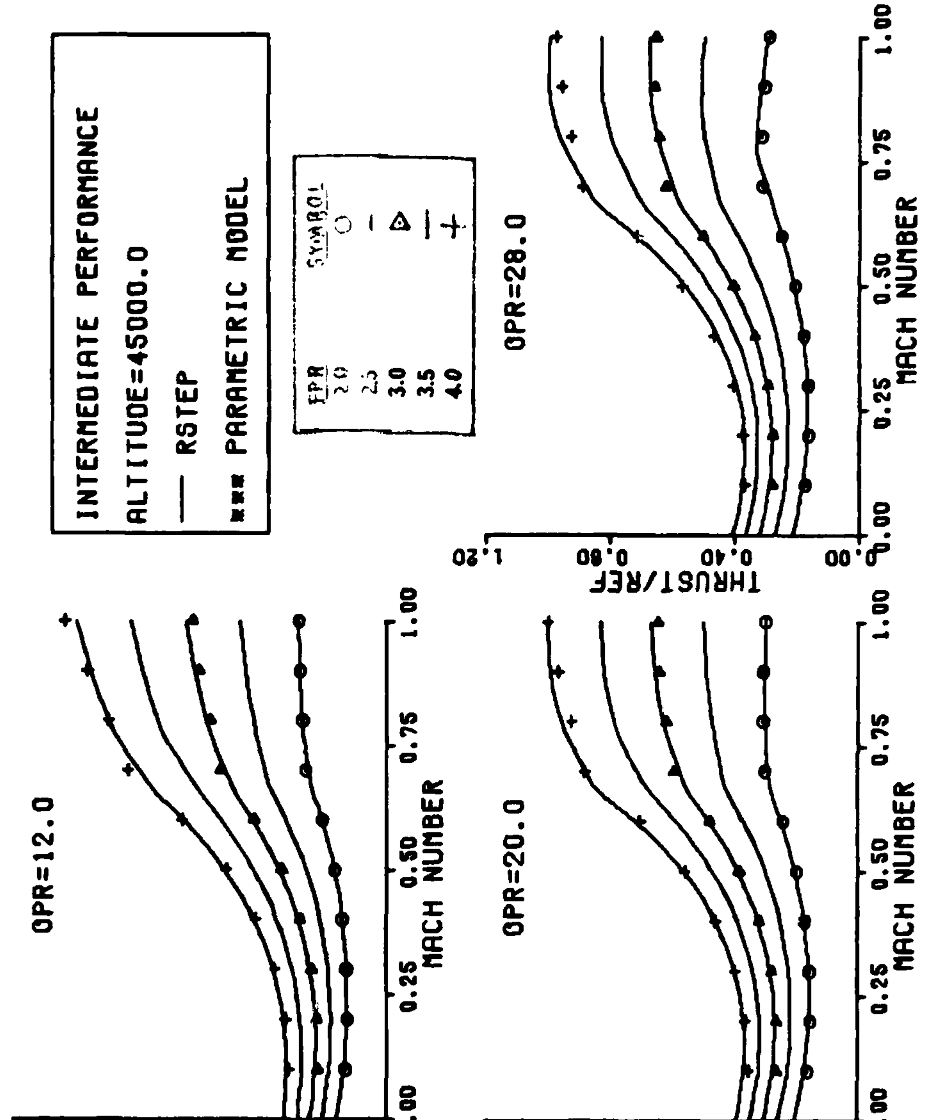


Figure 13. Intermediate Thrust Comparison at 45,000 Feet

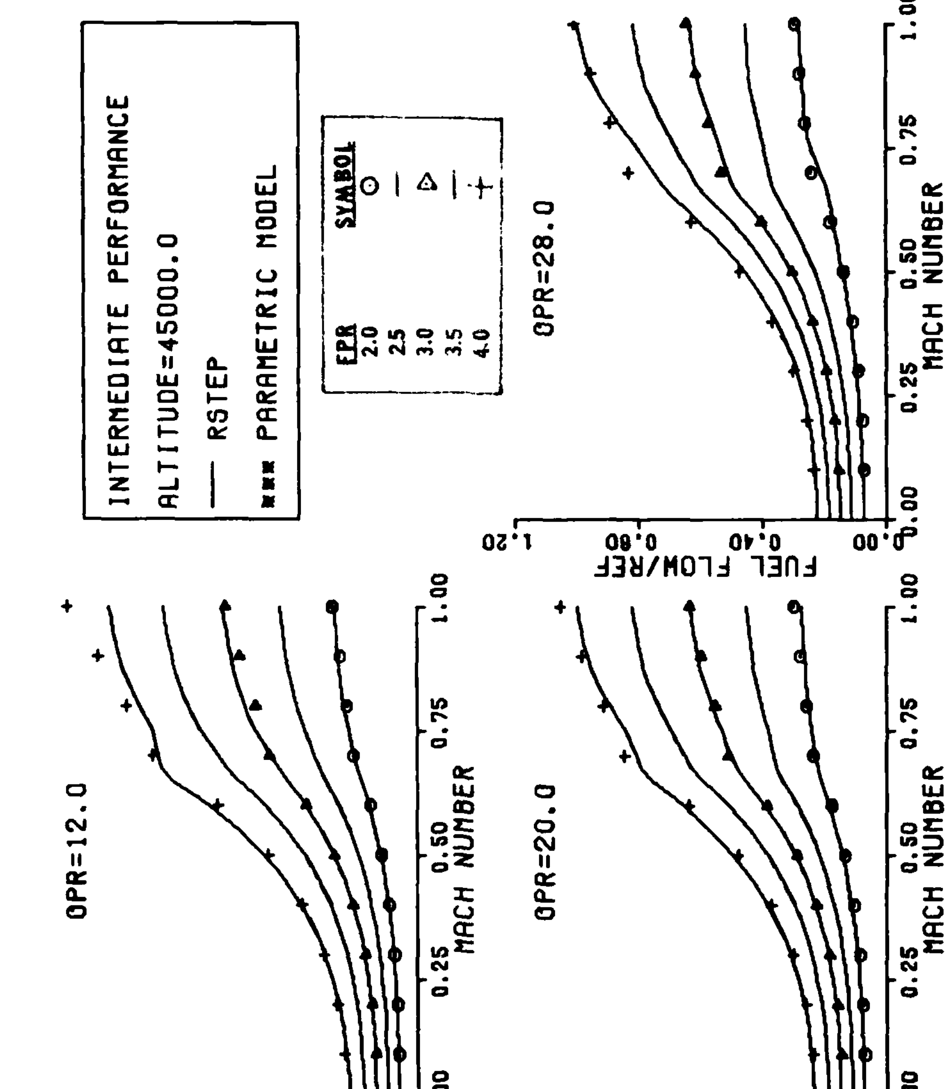


Figure 14. Intermediate Fuel Flow Comparison at 45,000 Feet

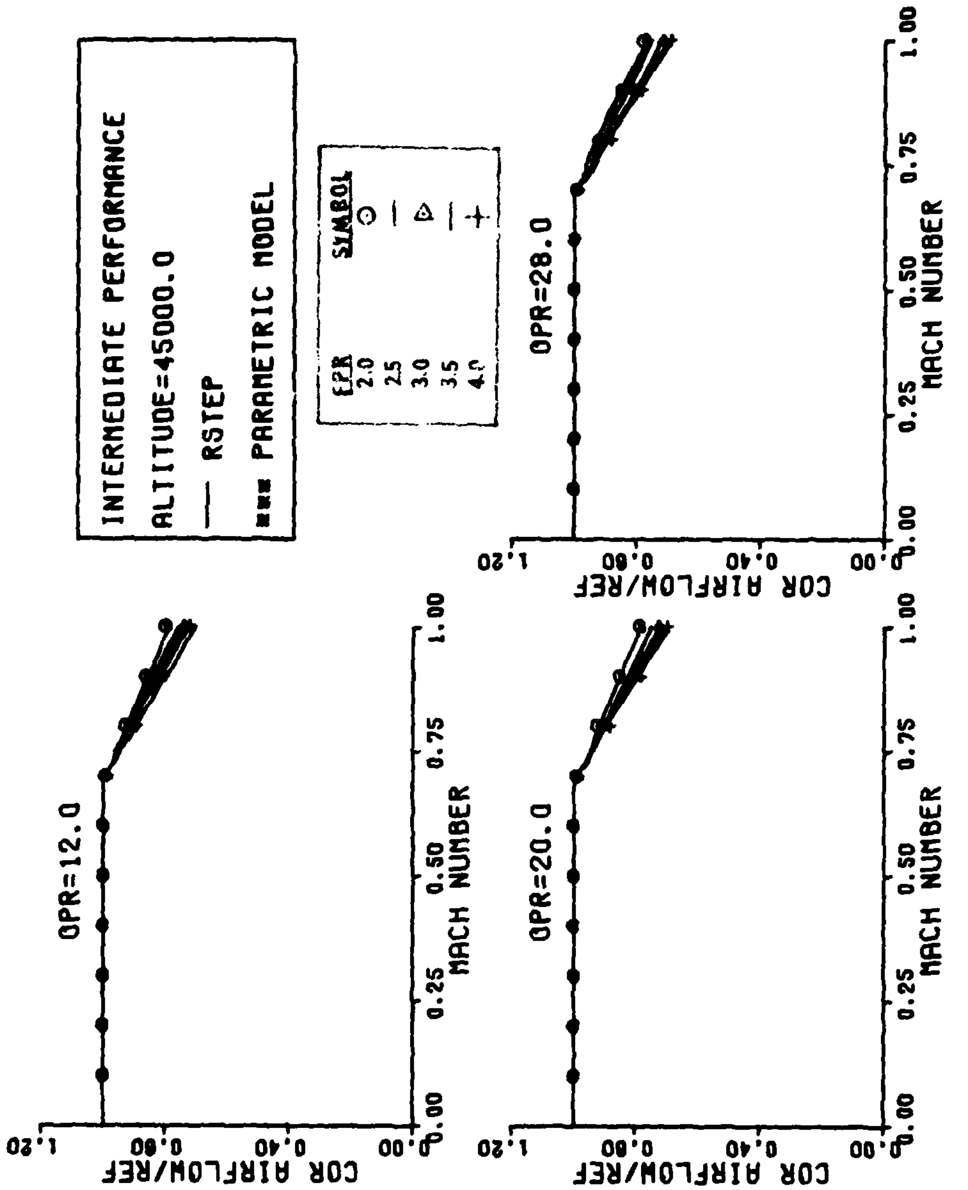


Figure 15. Intermediate Airflow Comparison at 45,000 Feet

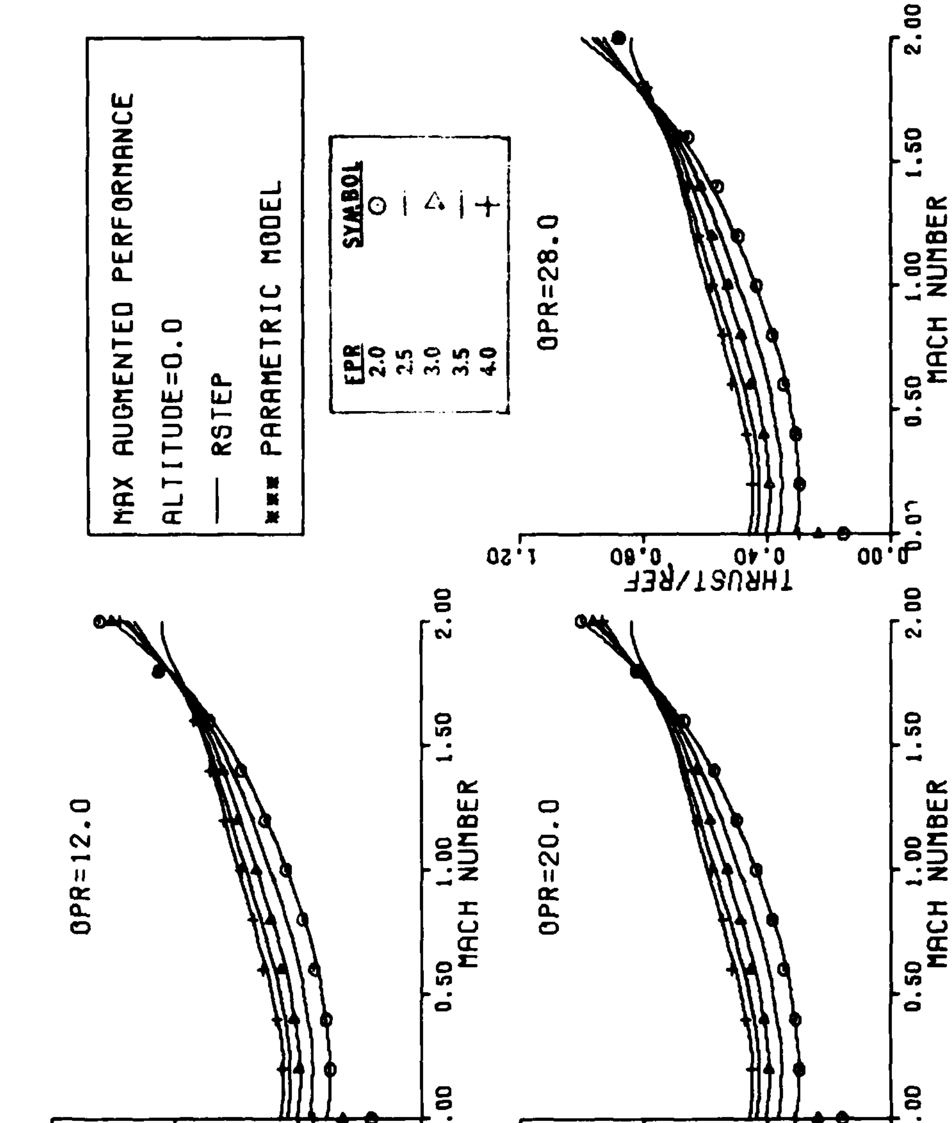


Figure 16. Max Augmented Thrust Comparison at Sea Level

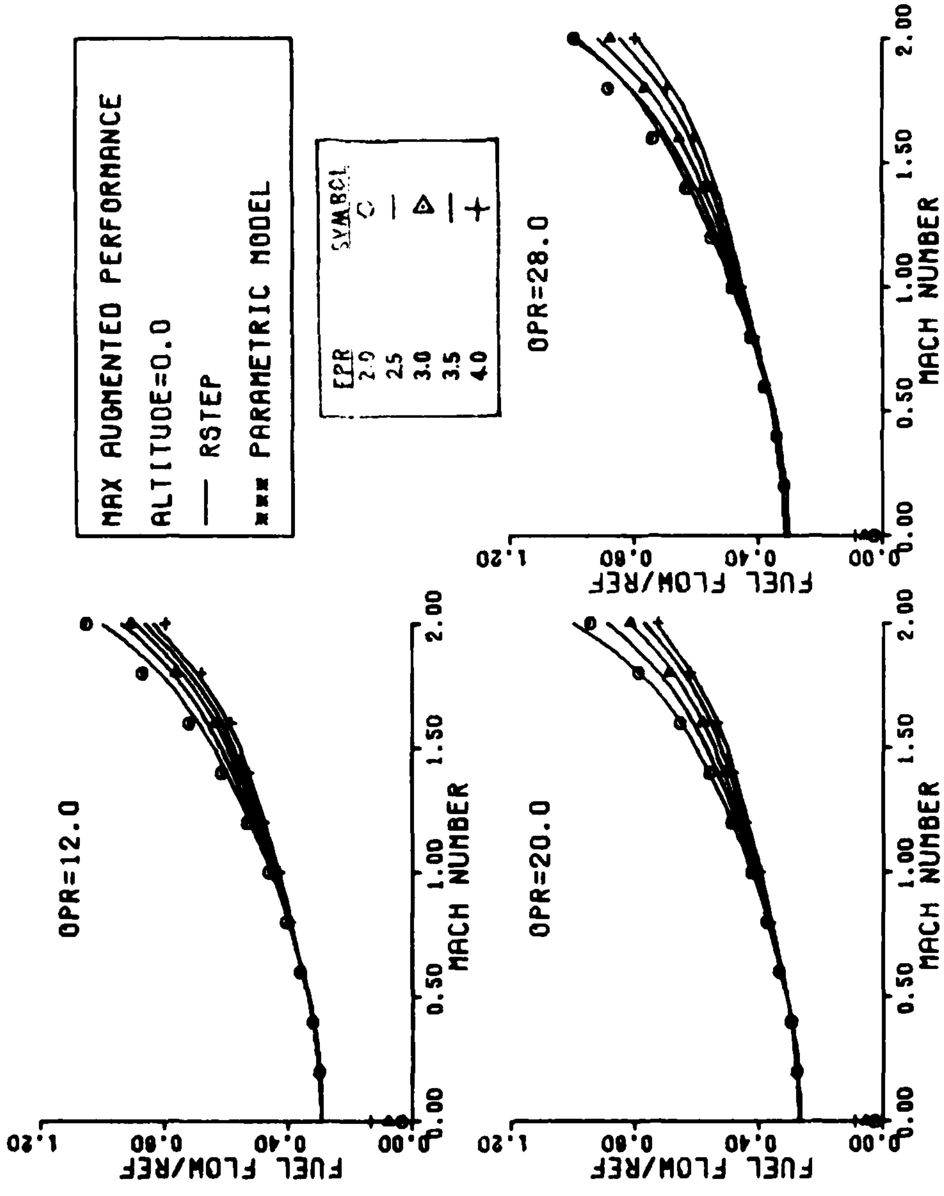


Figure 17. Max Augmented Fuel Flow Comparison at Sea Level

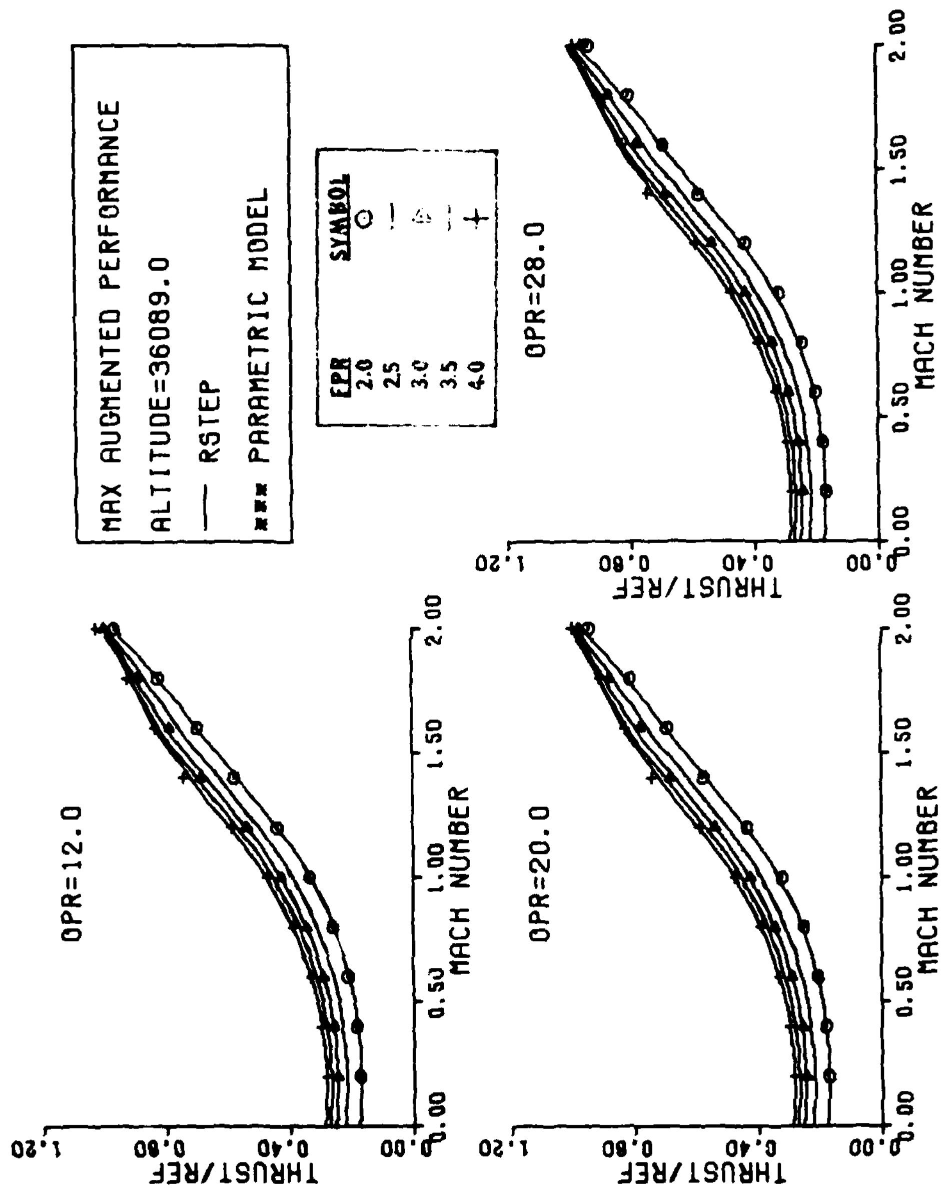


Figure 18. Max Augmented Thrust Comparison at 36,089 Feet

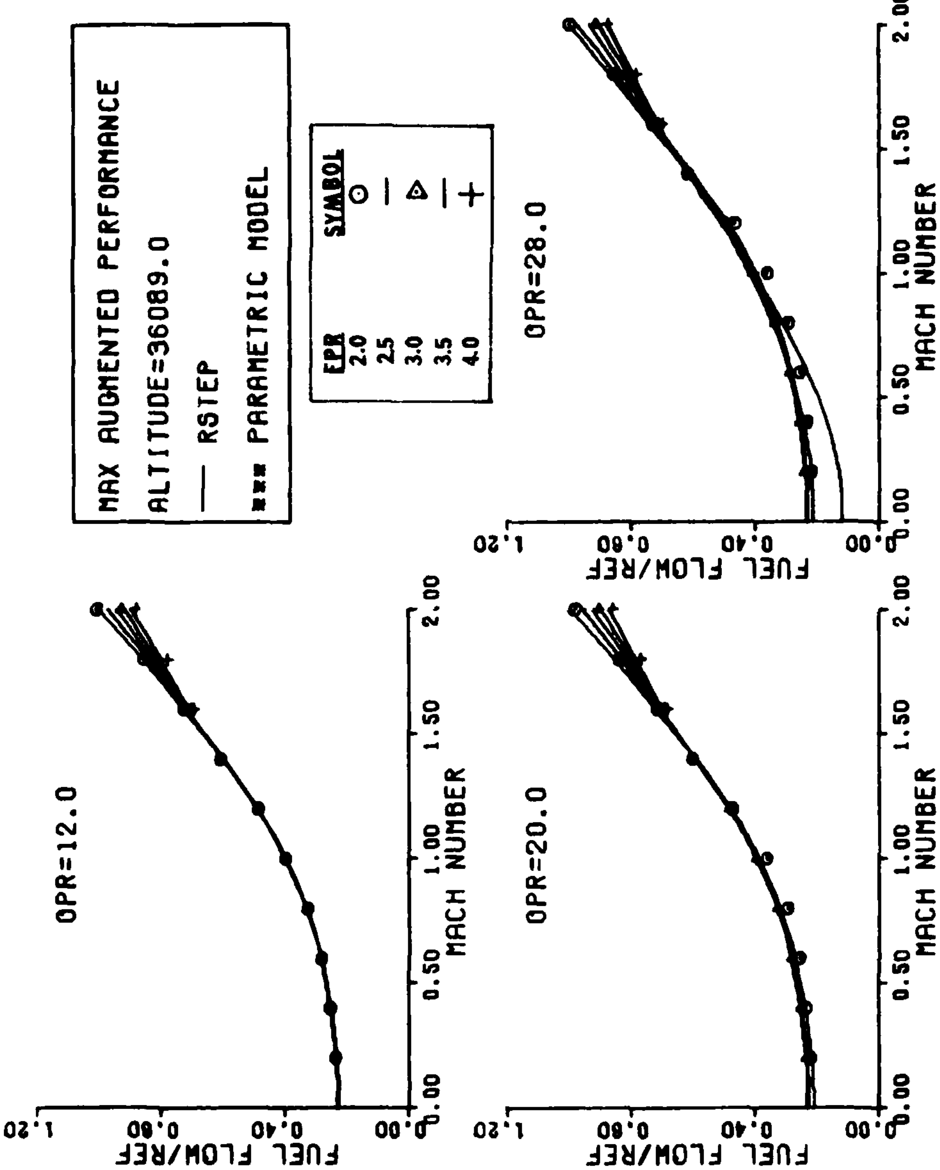


Figure 19. Max Augmented Fuel Flow Comparison at 36,089 Feet

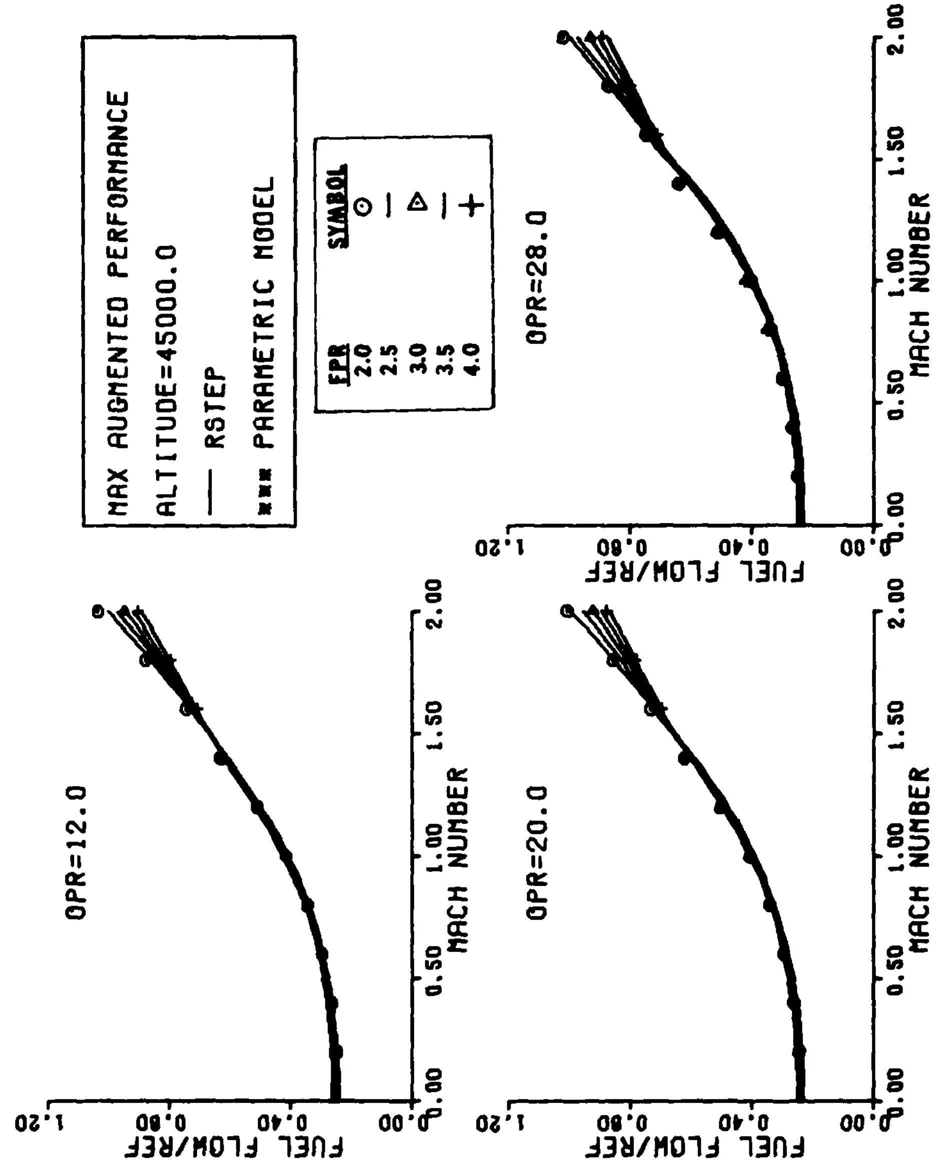


Figure 20. Max Augmented Fuel Flow Comparison at 45,000 Feet

c. Dry Part Power Performance Comparison

For part power comparisons, the presentation format has been changed to show a variation in thrust at a given Mach number and altitude. Variations in FPR and OPR remain the same. Only subsonic Mach numbers (0.0, 0.85, 0.90) have been selected for comparison since most dry part power operation falls in this regime. Airflow correlations were excellent and have not been included for this reason.

In examining Figures 21, 22 and 23, it is seen that RSTEP and the original simulation responses are almost identical. This area is considered one of the most critical portions of the RSTEP model. On one hand, accurate representations of dry, part power performance are vital to meaningful propulsion system evaluation, while on the other, this regime of engine operation is probably the most difficult to model.

d. Augmented Part Power Comparison

Again, comparisons are made at given levels of Mach number and altitude. Figures 24 to 27 depict these comparisons. For the conditions selected, the comparisons of RSTEP to the original engine simulation are excellent with the one exception being in Figure 27 at an OPR of 28.0 and FPR of 4.0.

It should be noted that the RSTEP model does not provide an indication of minimum AB power levels. Rather, RSTEP effectively extrapolates augmented performance to whatever power level is desired. Thus, in using this part of the model it would be wise to check and insure that desired augmented performance levels have not dropped below corresponding intermediate performance levels.

2. ERROR ANALYSIS

The direct comparisons shown in the previous section are of value to the engineer in that they not only permit an error in magnitude assessment, but also allow an evaluation of regression model trend and slope characteristics as well. Unfortunately, regardless of how many direct

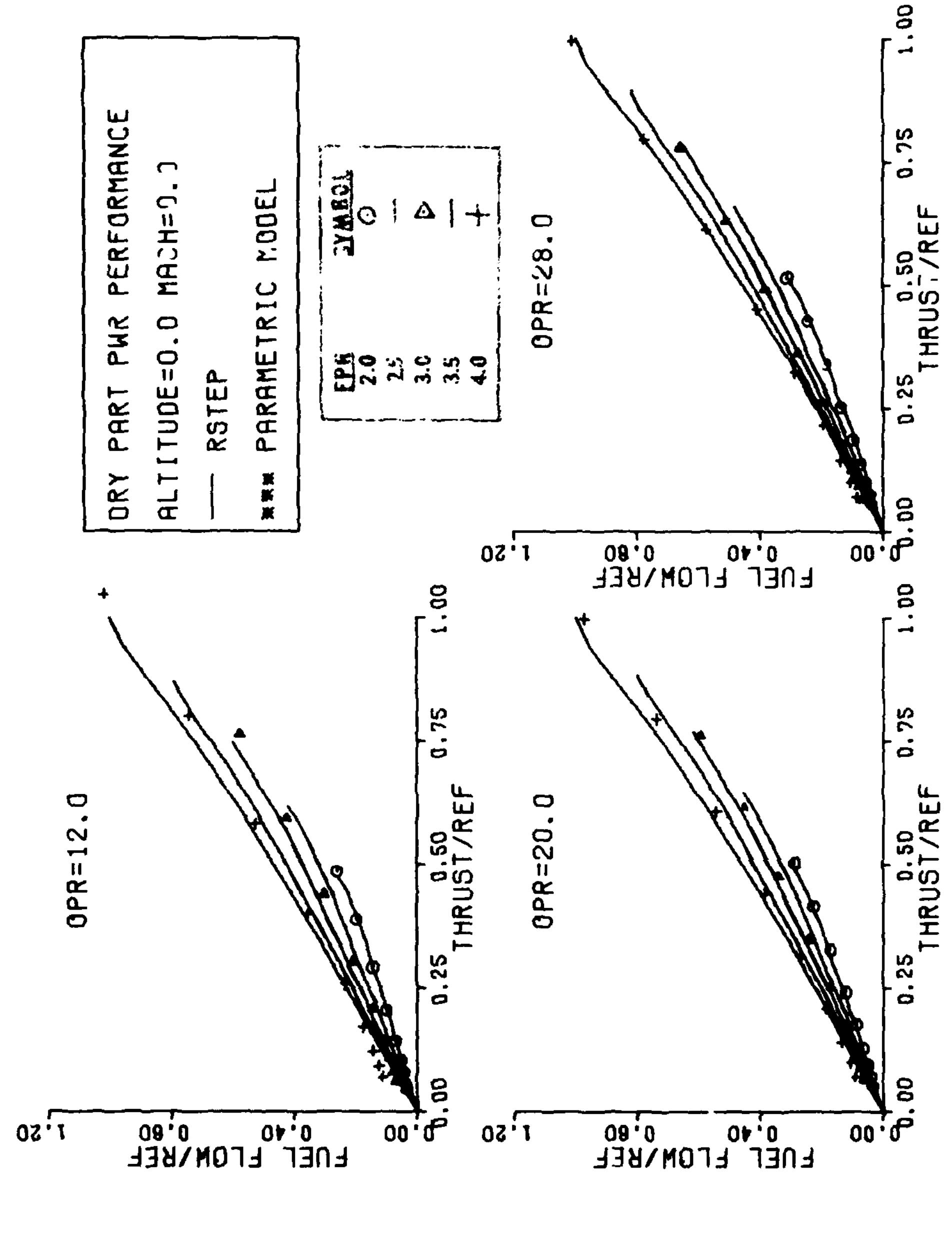


Figure 21. Dry Part Power Comparison at Sea Level

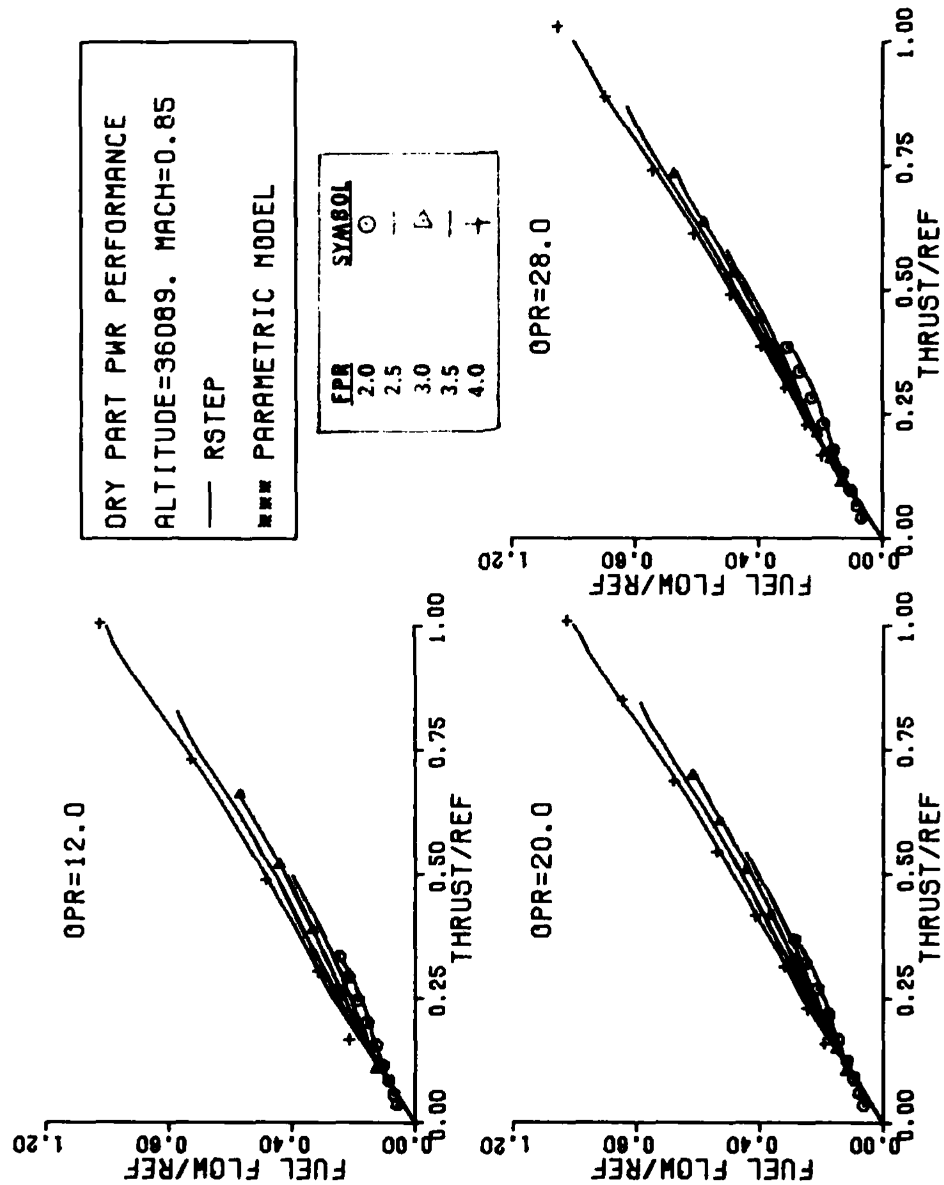


Figure 22. Dry Part Power Comparison at 36,089 Feet

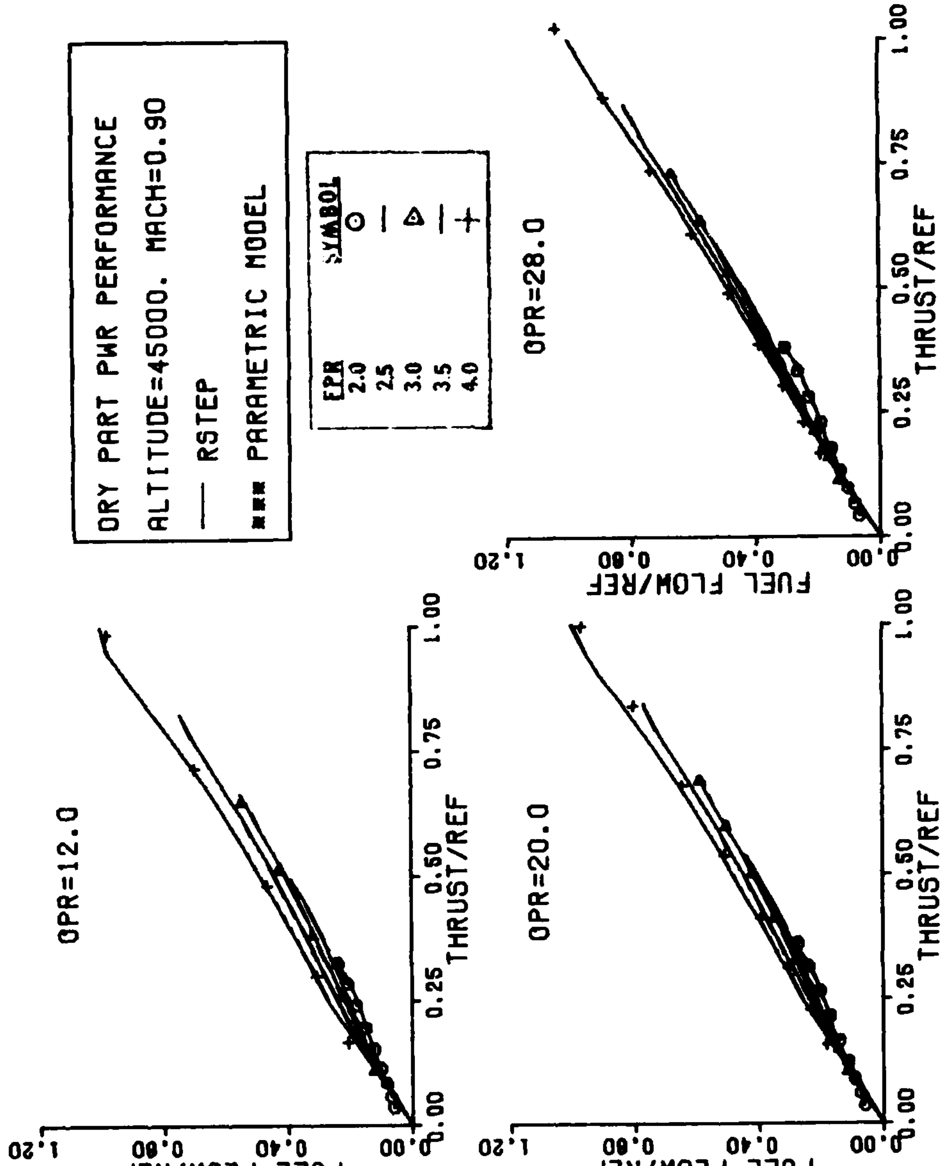


Figure 23. Dry Part Power Comparison at 45,000 Feet

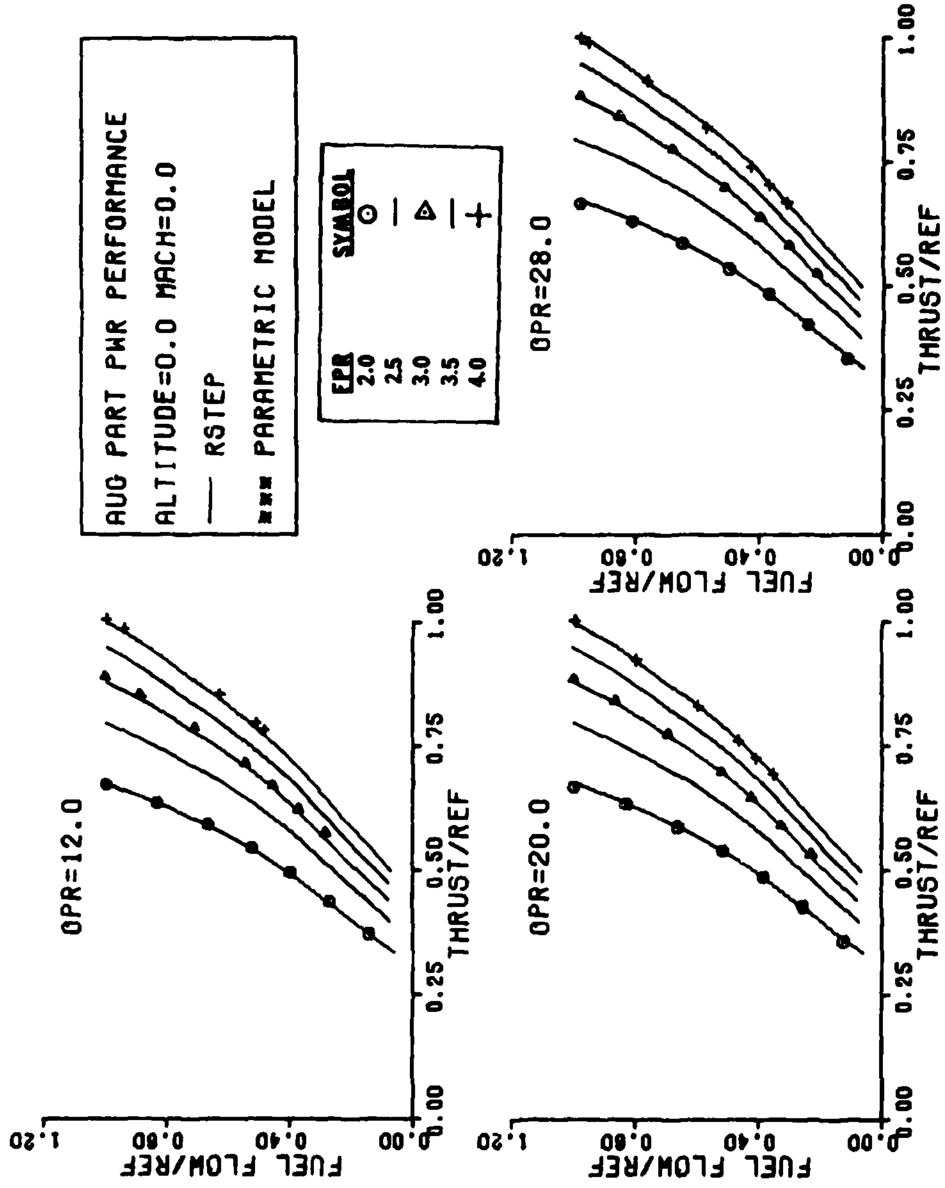


Figure 24. Augmented Part Power Comparison at Sea Level

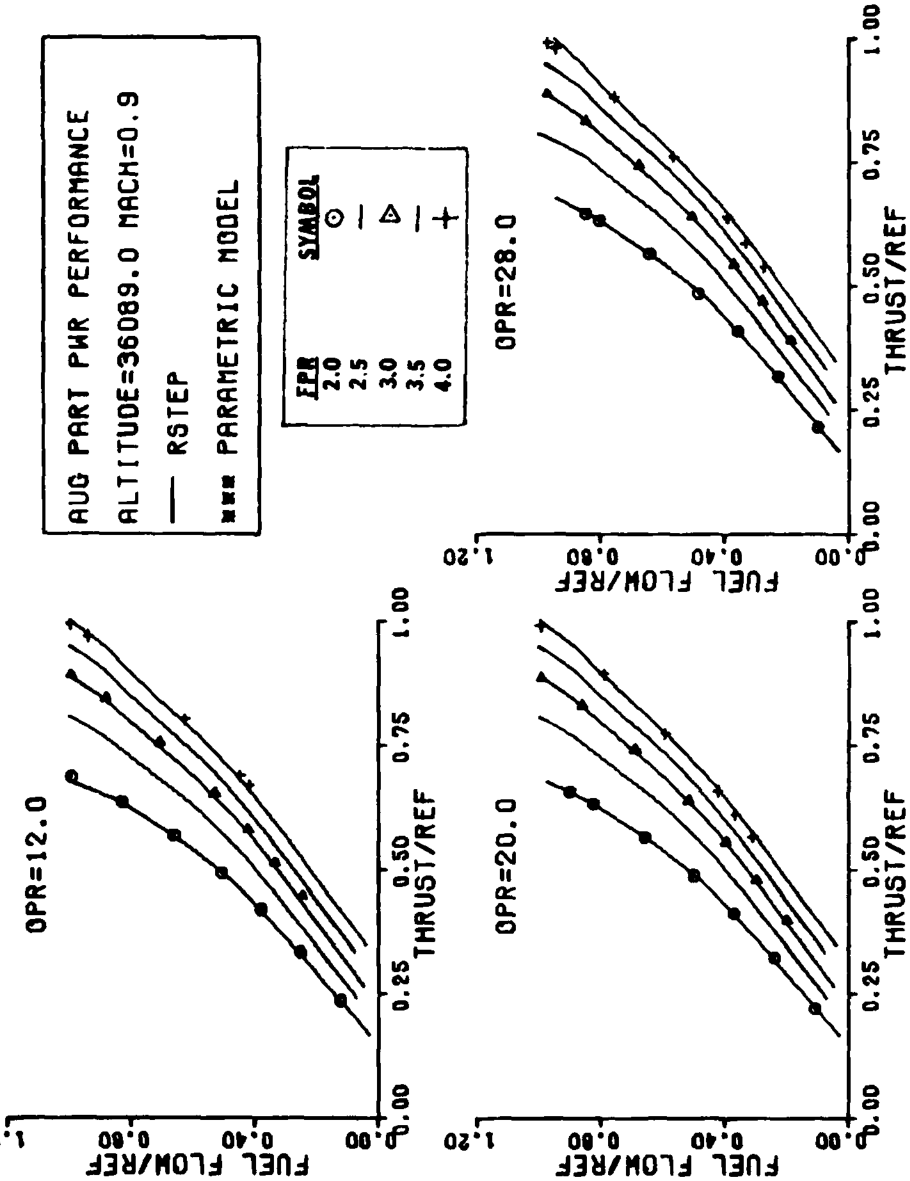


Figure 25. Augmented Part Power Comparison at 36,089/0.90

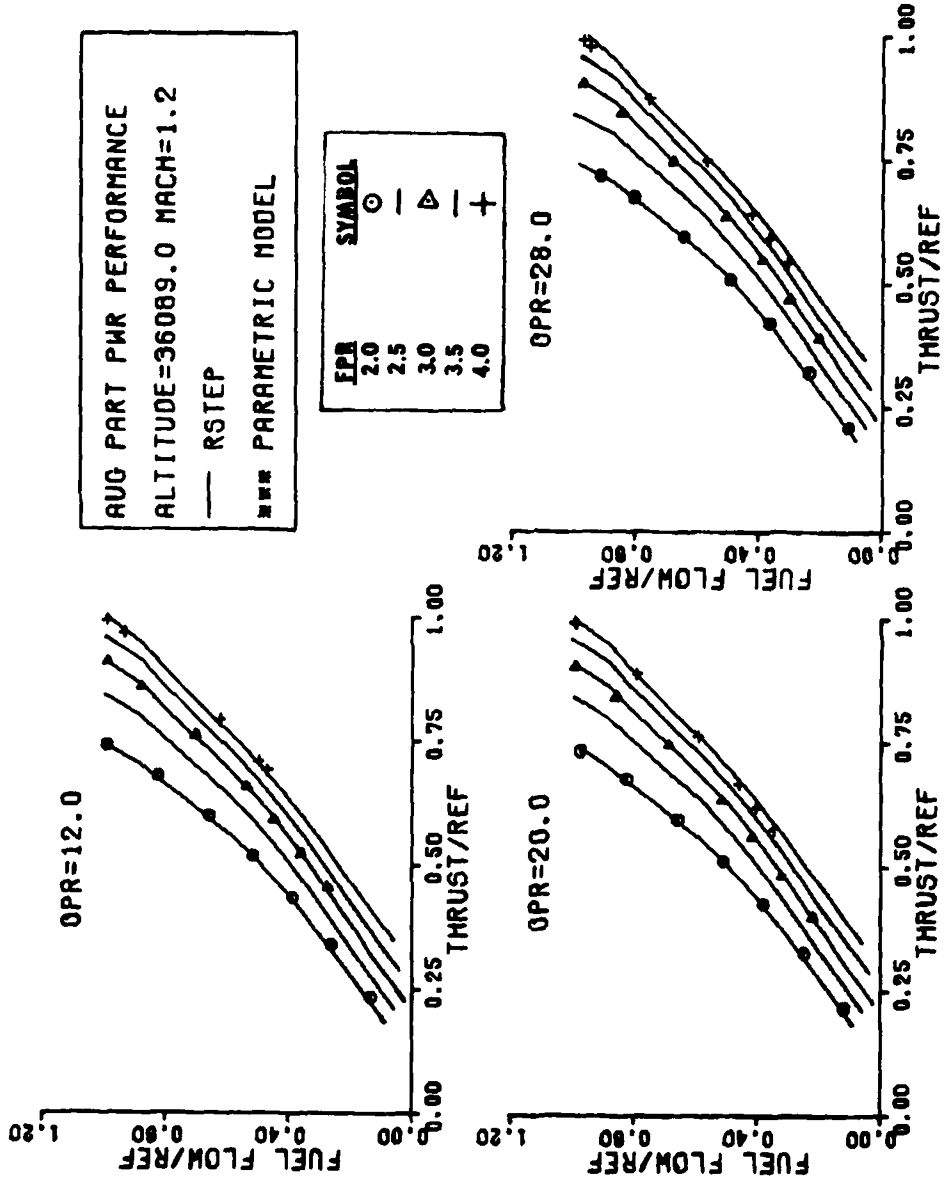


Figure 26. Augmented Part Power Comparison at 36,089/1.20

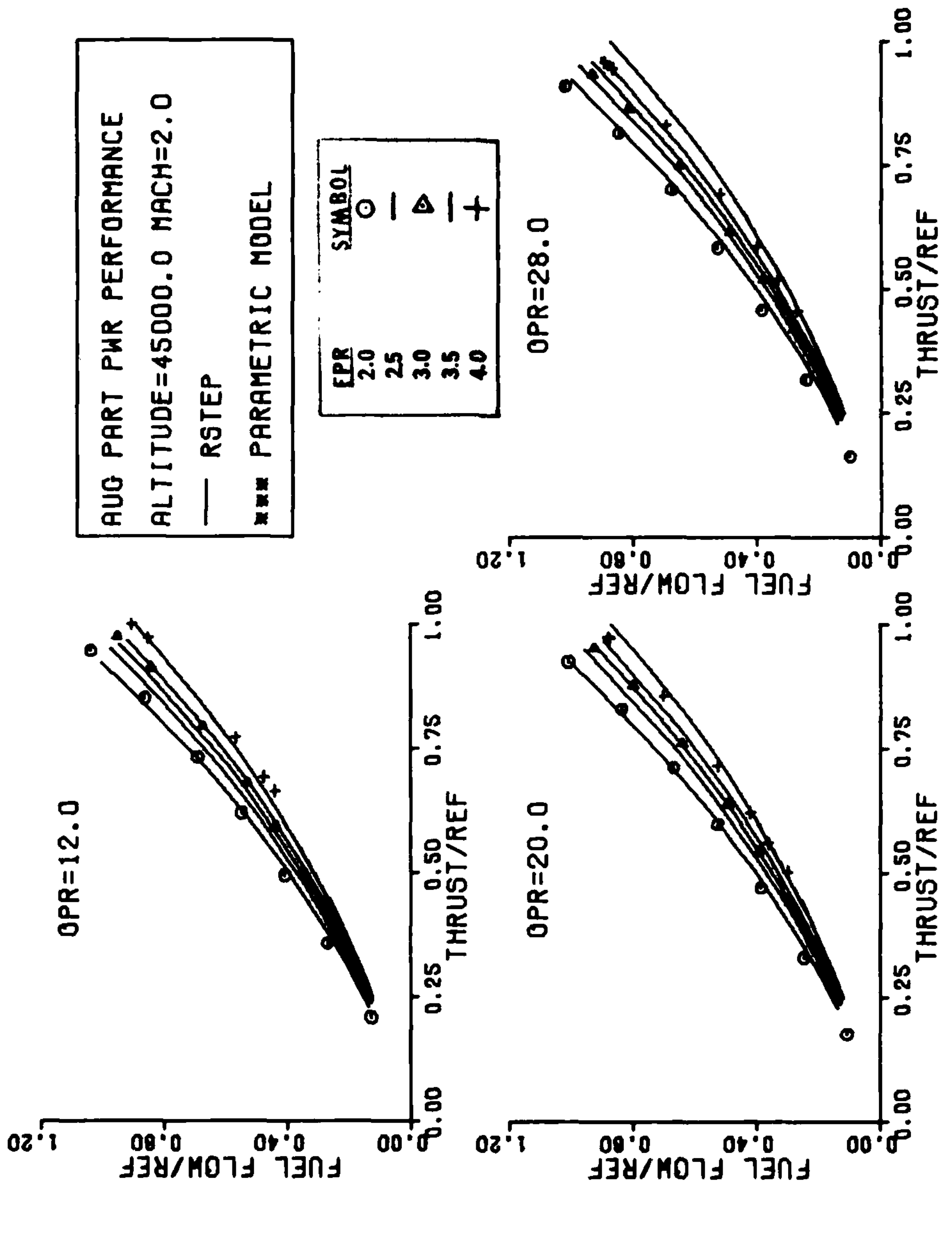


Figure 27. Augmented Part Power Comparison at 45,000/2.0

comparisons are made, there will always be some question about other areas of the design space. For this reason, an error analysis is provided for both the basic data set used in the regression model formulation and for a new, nonfitted data set. An examination of average error as a function power setting (GFN) is also provided.

a. Error Analysis of Fitted Data

Figures 28 and 29 depict the error distribution of the data used in generating the regression model for dry and augmented performance, respectively. Fuel flow has been selected for use in the error analysis since it was the most difficult parameter to accurately represent. For dry performance (Figure 28) each bar represents the percentage of points that fall in an error band of ±1/2 of a percent. As an example, for the first bar in Block 1 roughly 23 percent of the total of 810 points used in the regression model have an error of less than or equal to ±1/2 percent when compared to the original engine simulation. For the second bar approximately 20 percent of data had an error of between ±1/2 to ±1.0 percent. Or, considering both bars, 43 percent of the regressed data had an error of ±1 percent or less for Block 1.

The error analysis for Blocks 1 and 2 shows a fairly consistent trend, Blocks 3 and 4 do not. This is believed to be at least in part because of the relatively low number of points used in the sample for these blocks. The error analysis for augmented performance, Figure 29, shows a constant trend in error distribution for all blocks. Note, however, that intervals selected for evaluation represent one percent intervals rather than the 1/2 percent used in Figure 28.

b. Average Error as a Function of Power Setting

While great emphasis is placed on reducing both maximum and average percent error, the least square procedures used to select regression equation coefficients are, in fact, geared to reduce the difference between the calculated value

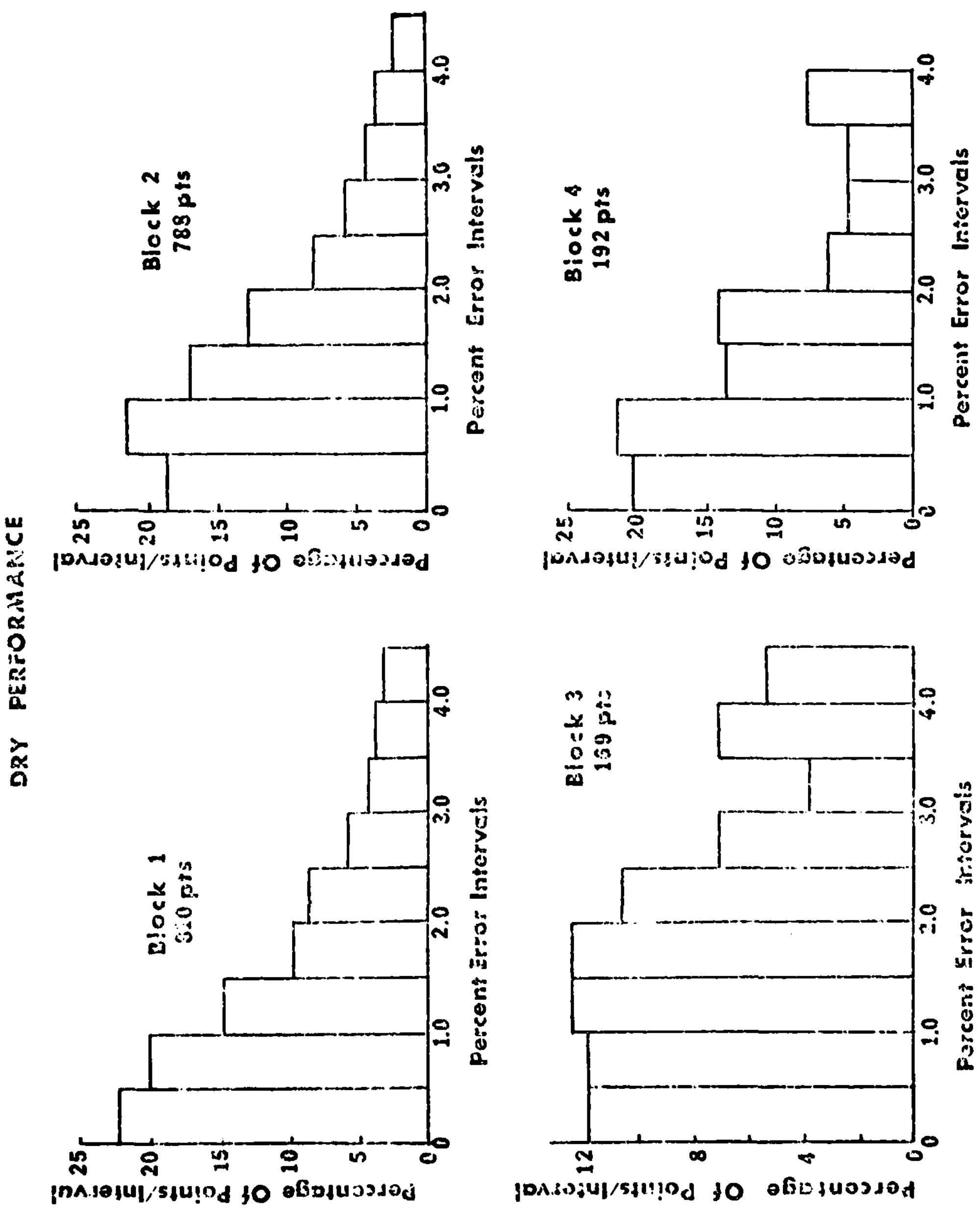


Figure 28. Error Analysis for Dry Fuel Flow

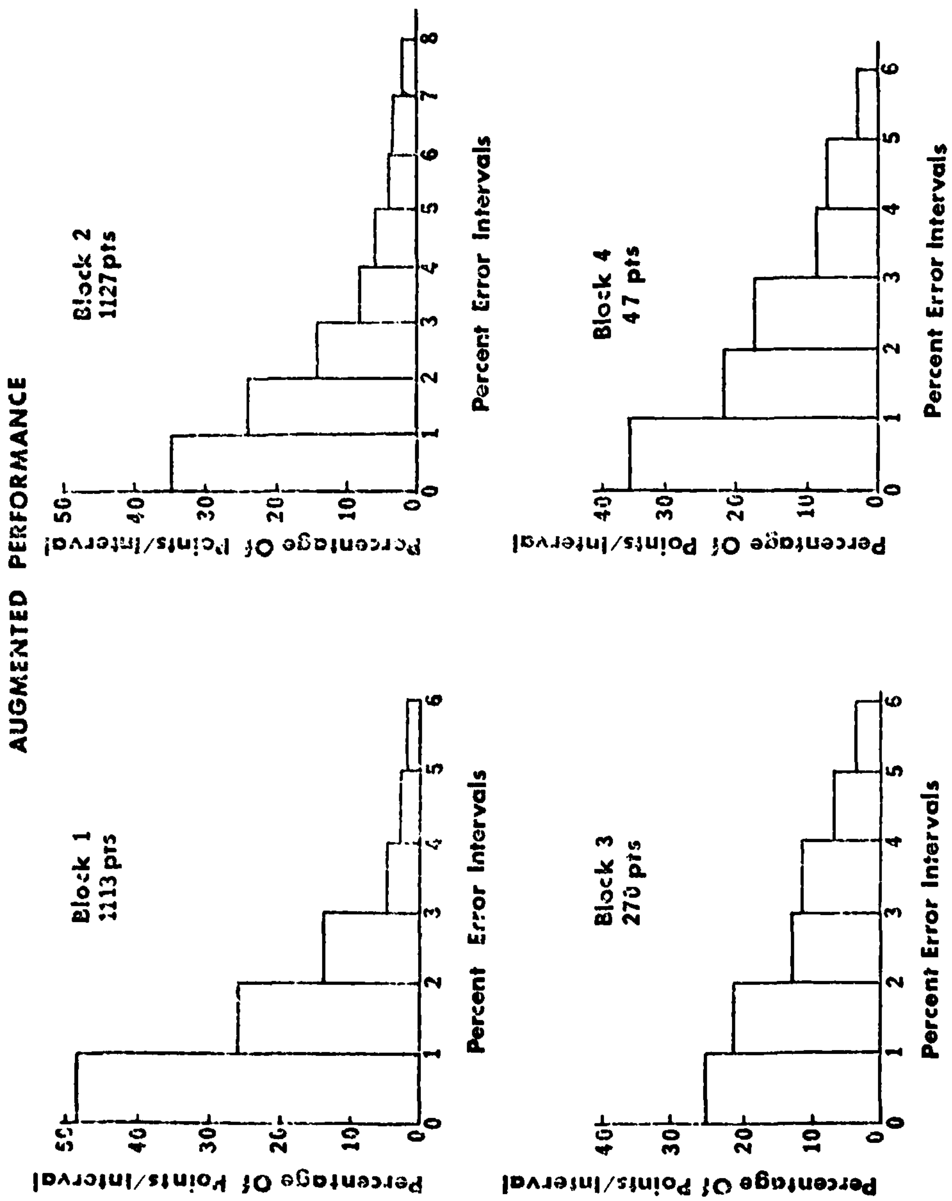


Figure 29. Error Analysis for Augmented Fuel Flow

of the dependent variable and its actual or input level. The minimizing of this difference or residual is not equivalent to minimizing percent error. Rather, if the residual is the difference between two large numbers the percent error may be small, but if the same residual is between two small numbers, the percent error may be relatively large.

For instance, for intermediate thrust levels the magnitude of the RSTEP dependent characteristics are normally at or close to their largest value. As thrust is decreased the magnitude of each dependent variable is also decreased. In trying to develop a regression equation model for each dependent characteristic, the Least squares procedure will minimize the differences between the fitted equation form and the actual value input. In most instances, the residuals tend to become approximately equal in magnitude over the entire power hook. Thus, since the residuals are roughly constant in magnitude, percent error (residual divided by the dependent value) tends to increase with reduced power setting. Figures 30 and 31 show the increase in average error for several of the dependent characteristics as power setting is reduced. Note that the symbols used in these charts are to identify the various dependent parameters and do not represent points at which the average error was calculated.

In reviewing these charts, two observations should be made. First, using the procedures previously outlined for RSTEP, the resulting regression model representations result in the lowest average error occuring at the intermediate and max augmented power conditions. This error bias is not seen as necessarily detrimental since accurate performance modeling is critical at high power conditions. In addition, significant increases in average error do not occur in fuel flow (most critical parameter) until GFN levels fall below 0.5 to 0.6. Most engines will be in a power range above these levels. The one major exception being a holding pattern. The second point to be made is that, in very low (idle) power settings, the absolute fuel flow levels are so low in comparison to other operating conditions that higher levels of average error can be tolerated without significant impact on study results.

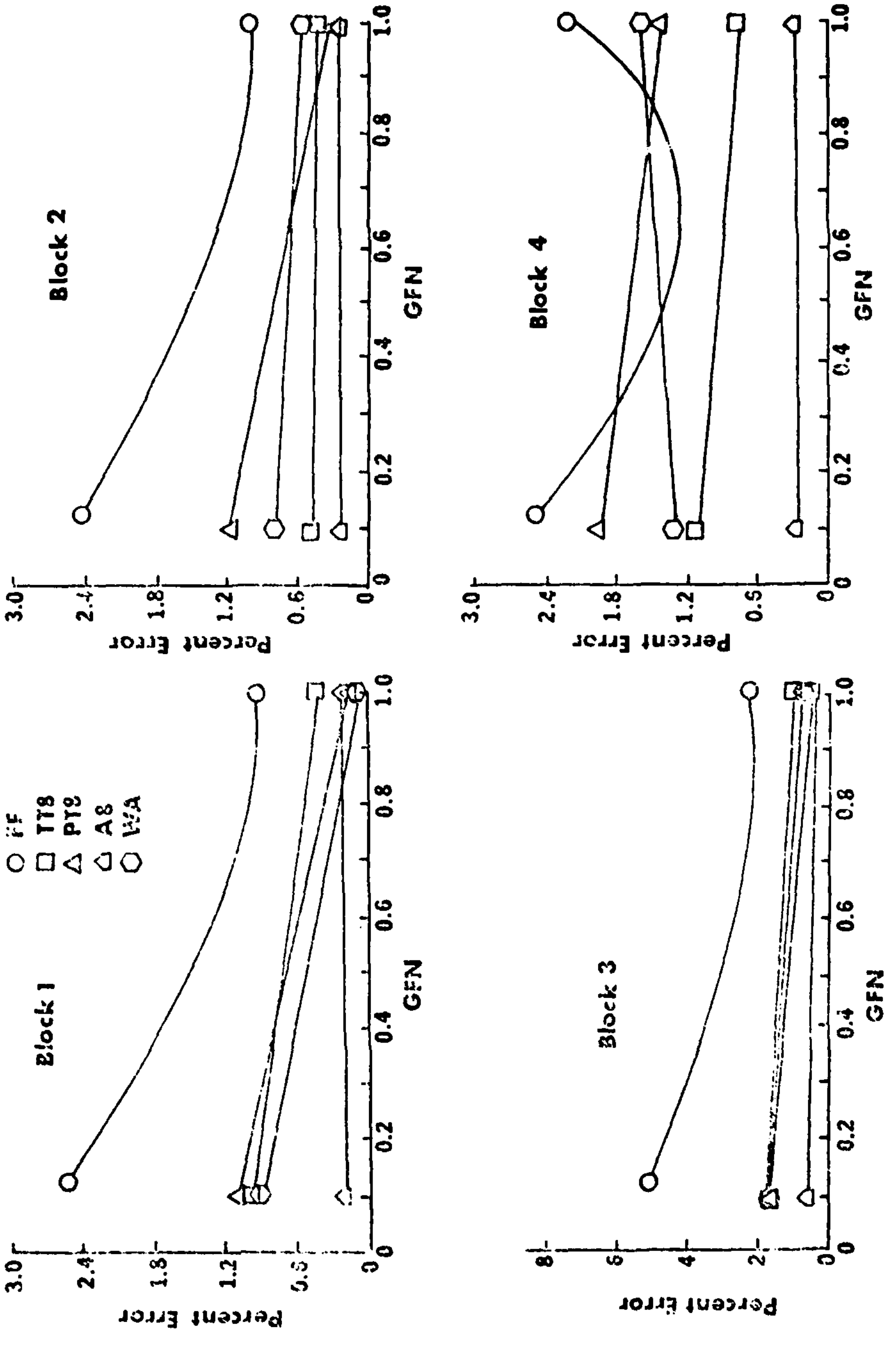


Figure 30. Average Error as a Function of Dry Power Setting

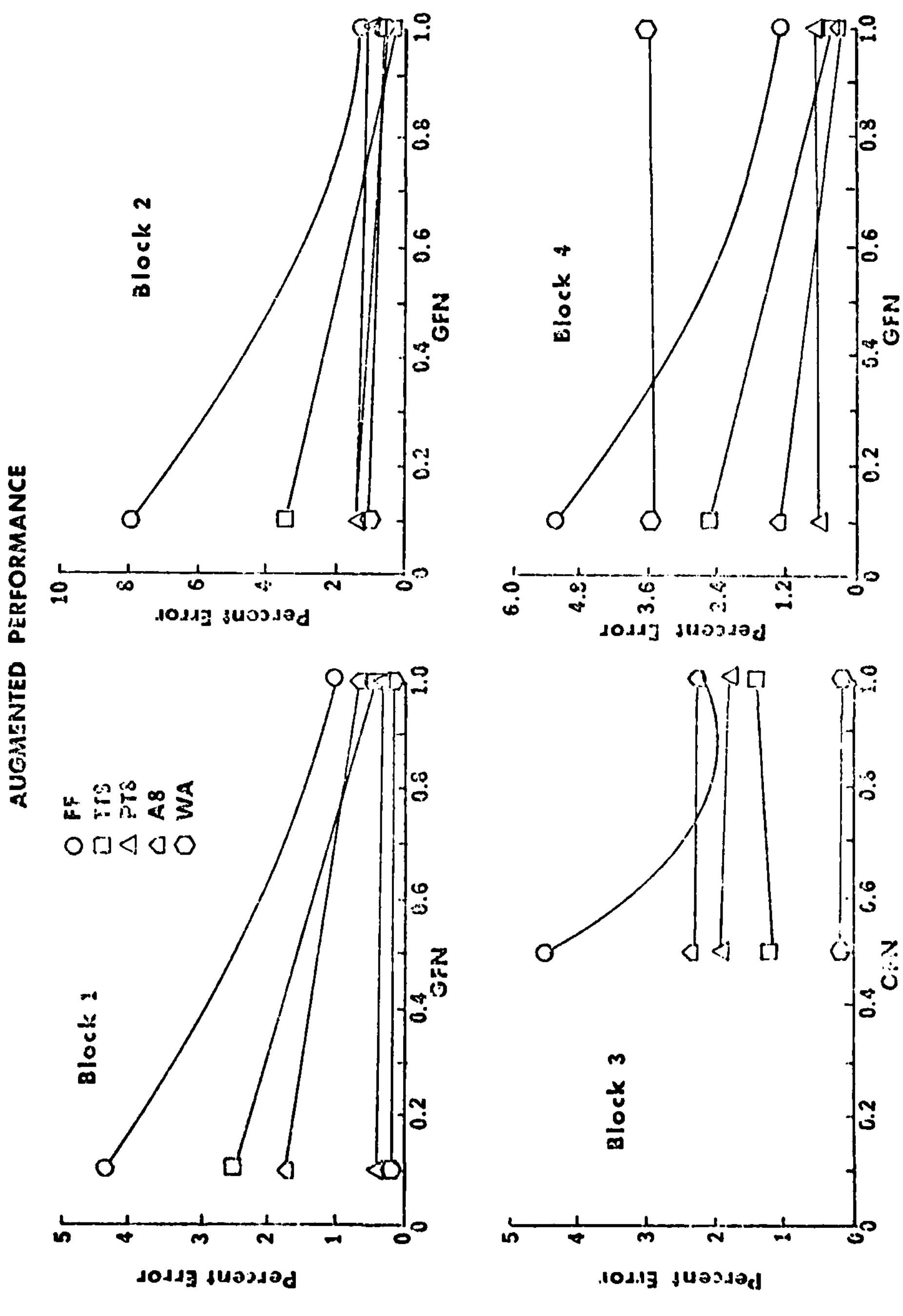


Figure 31. Average Error as a Function of Augmented Power Setting

c. Error Analysis for Nonfitted Data and Ram Recovery Investigation

The final test of the RSTEP model is to evaluate the model against the original engine simulation using a new data base which was not involved in the development of the RSTEP regression equations. In addition, this is also a convenient point to evaluate the effect of a specified level of ram recovery on overall simulation error (see Section IV, Paragraph 8).

To carry out this portion of the analysis four separate comparisons were made. Two dry performance data sets were generated over the Mach number/altitude range shown in Figure 32. One was generated using a Mil Spec recovery and the other used the recovery curve shown in Figure 33. A 7x7 Latin square was used to select the data points to be compared. FPR and OPR were varied in the Latin square using the same ranges as before (see Figure 2). From Figure 32, it is seen that for dry operation the Mach number range of interest has been reduced to between 0.40 and 1.2. In most applications, this region is of most interest during dry operation. By reducing the size of the test region, a more thorough sampling and evaluation can be conducted. A similar approach was employed for the augmented regime. Two augmented data sets were generated for the two recovery levels through the use of a 7x7 Latin square. The augmented test region was altered from that used in the dry comparison to include Mach numbers up to 2.0.

The results of the error analysis and recovery comparisons are shown in Figure 34 for dry performance and Figure 35 for augmented performance. All error distributions are well-behaved indicating a satisfactory level of sampling. It is seen that for the dry performance of Figure 34, the two error distributions are almost identical indicating that specifying a level of ram recovery other than Mil Spec does not introduce additional error into the analysis for dry performance. For the augmented performance comparison in Figure 35, it is seen that the average error level increases slightly for the specified ram recovery levels. However, this difference should not have a significant impact on overall propulsion assessment.

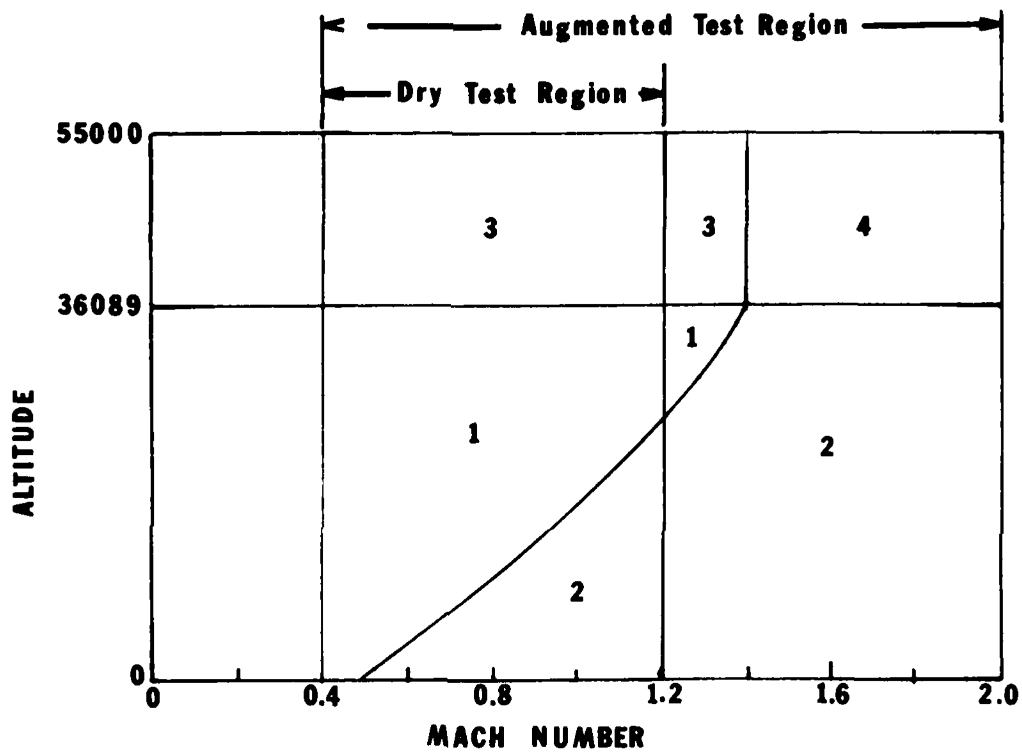


Figure 32. Non-Fitted Data Test Region

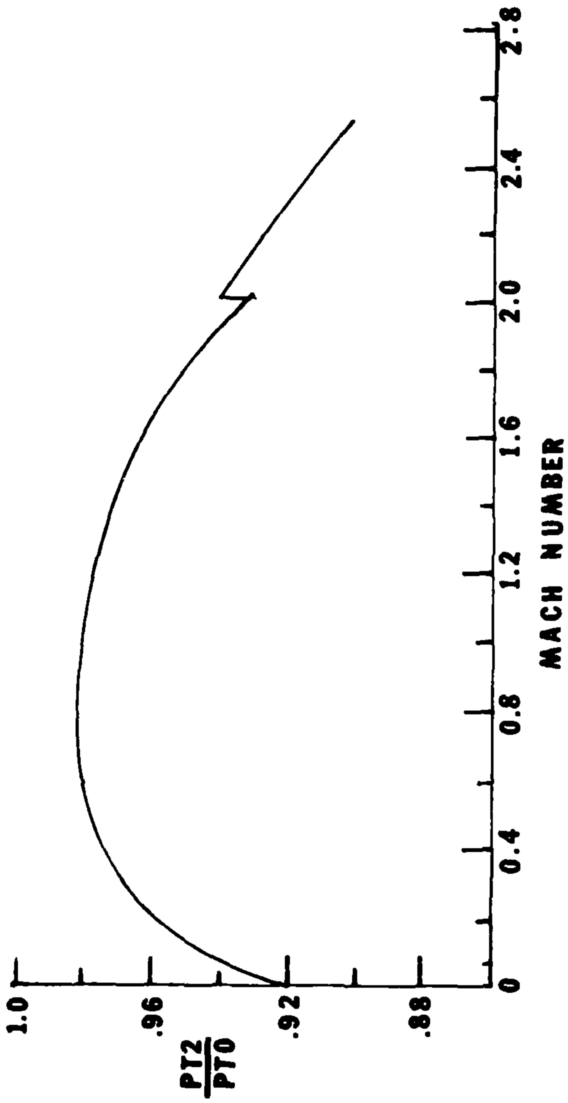


Figure 33. Ram Recovery

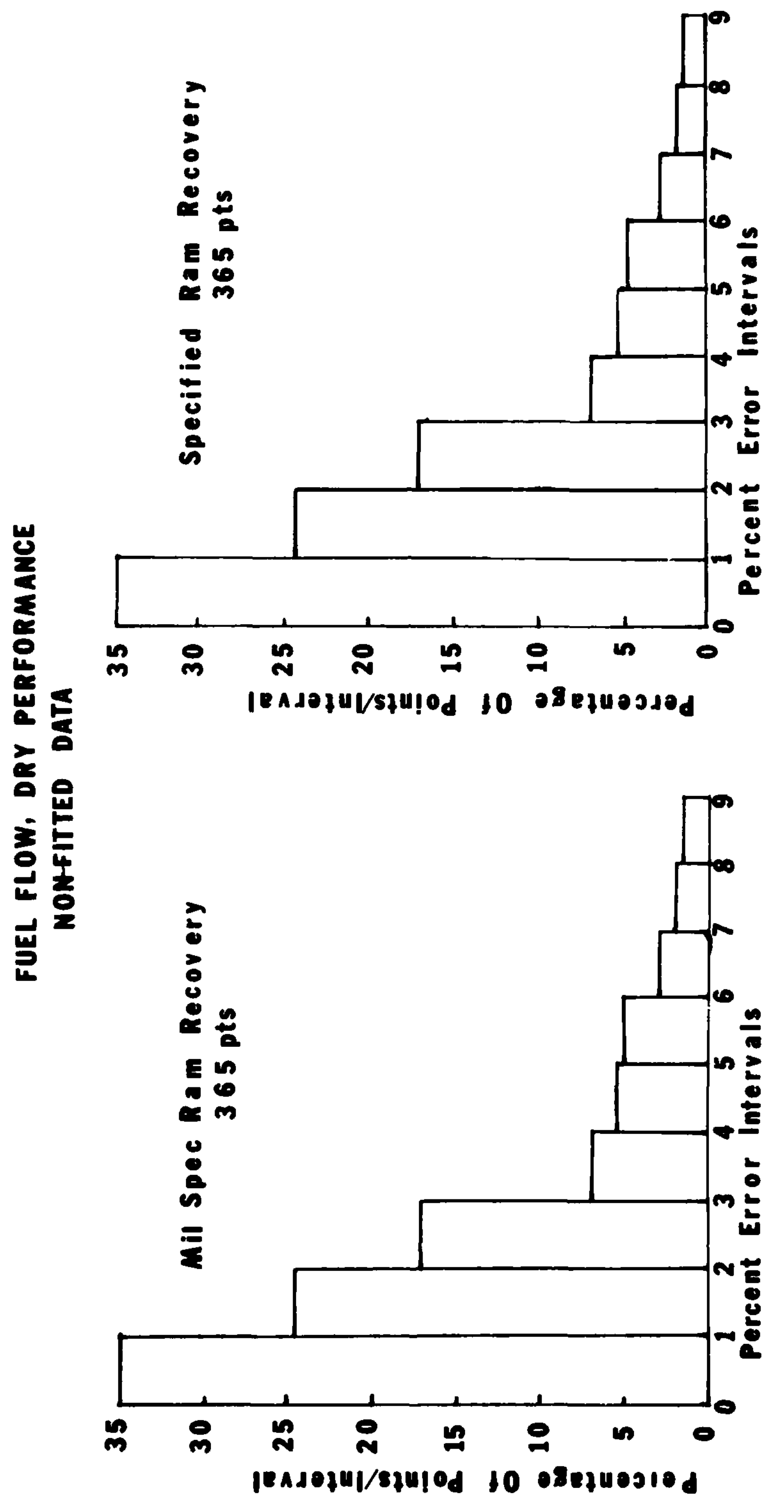


Figure 34. Composite Error Analysis-Dry Performance

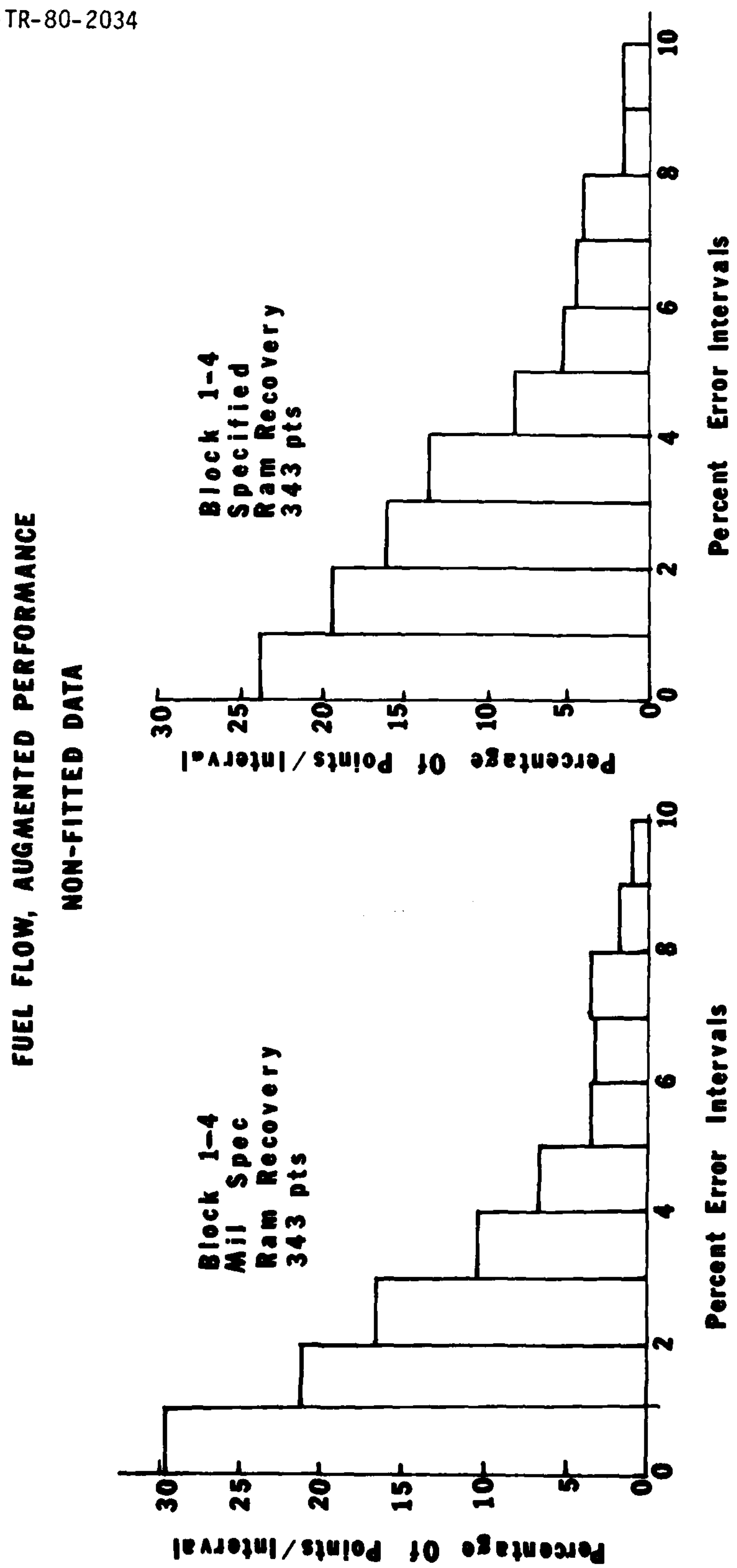


Figure 35. Composite Error Analysis-Augmented Performance

3. ERROR ANALYSIS OF ENGINE WEIGHT AND GEOMETRY CHARACTERISTICS

To make RSTEP complete in terms of its capability to support conceptual analysis efforts, a weight and geometry regression model was developed as a function FPR, OPR and design airflow (SLS). As can be seen from Figure 36, most engine weight and geometry characteristics can be modeled to within 1/2 percent of their actual valves. This is considered more than satisfactory for conceptual analysis work.

4. SIZE/SPEED/COST COMPARISON

Since RSTEP was constructed to reduce conceptual analysis data generation costs, the final assessment is then in dollars, deck size and data points per second. Table 9 summarizes this information. Both RSTEP and the original engine simulation have several modes of operation. For comparison purposes the fastest mode of data generation (this mode is normally used in conceptual analysis work) will be used for the parent engine simulation with RSTEP operating in a comparable mode plus one other. The power hook mode is the fastest mode of operation for both parent model and RSTEP. As can be seen from the table, data generation costs have been reduced by a factor of fifteen to one. Data points per unit time on the central processor is approximately forty to one. The one disappointing feature of the RSTEP model is the program size. This core size requirement may preclude direct coupling with the aircraft design and mission analysis program on many computer systems.

Even though the program size is not promising, an evaluation was done with RSTEP in a direct couple mode (Thrust Match) to assess deck speed in this area. The deck speed of 75 points per second would not seem to be satisfactory in comparison to an interpolation routine working with a previously generated set of propulsion tables. However, with certain modifications, RSTEP speed in the Thrust Mode could be improved particularly for climb/cruise optimizations. It should also be noted that in the direct coupling of RSTEP to an aircraft design and mission analysis program no additional interpolation errors are introduced as in the case with a tabular set of engine data.

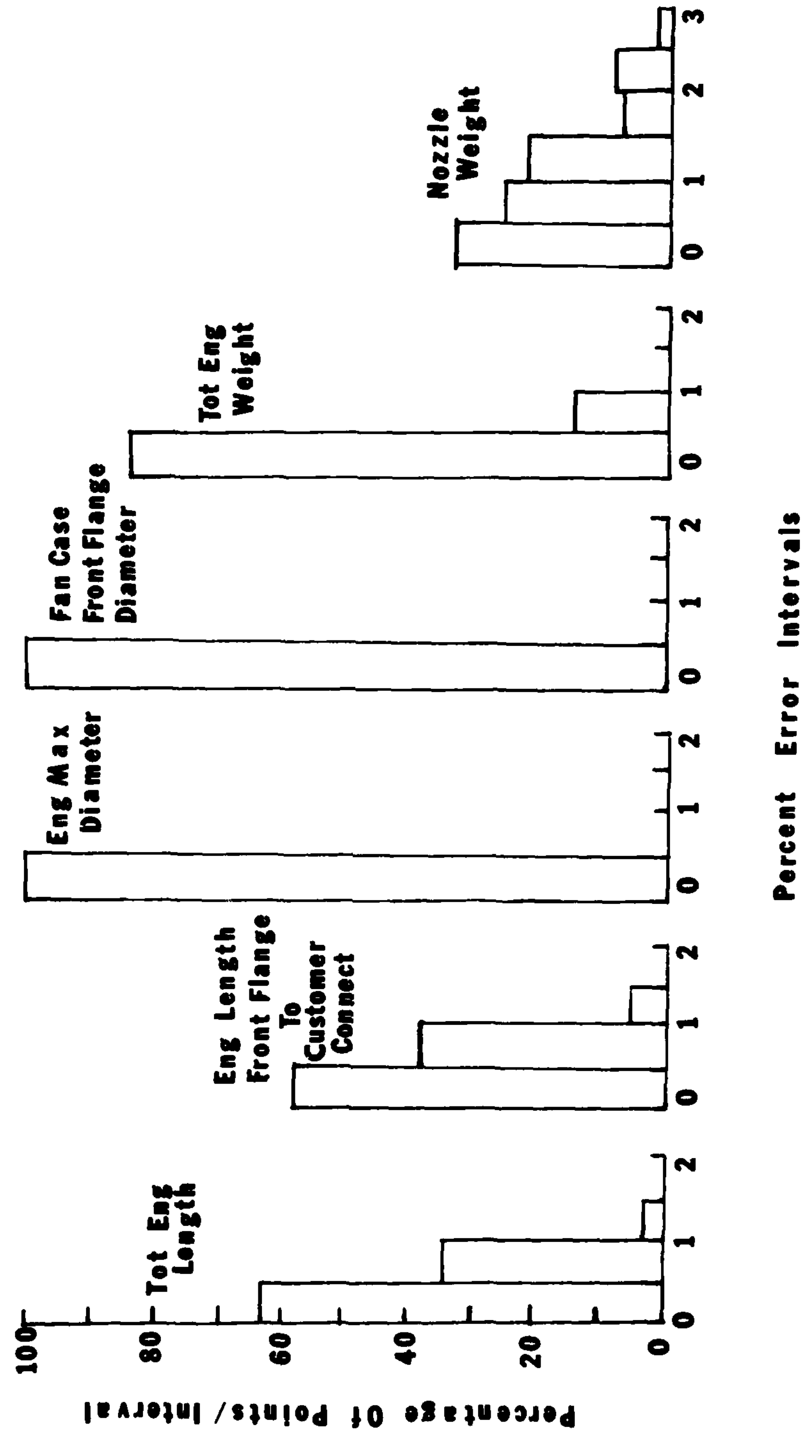


Figure 36. Error Analysis for Engine Weight and Geometry

TABLE 9

SIZE/SPEED/COST COMPARISON

	MODE	SIZE	SPEED	COST PER 100 POINTS*
BASELINE DECK	POWER HOOK	144,000 Octal	3Pts/Sec	$2.60
RSTEP	THRUST MATCH POWER HOOK	56,000 Octal	75 Pts/Sec 125 Pts/Sec	$0.29 $0.17

*CDC 6600 Computer System

SECTION VI

SUMMARY AND CONCLUSIONS

The cost savings associated with using a regression model of turbine engine performance is seen to be considerable. In addition, the accuracy levels demonstrated are considered satisfactory for conceptual design/preliminary analysis efforts. It is therefore unfortunate to also conclude that at least for a class of propulsion systems, regression modeling is not considered practical.

The amount of subdivision and data generation required to achieve an acceptable level of accuracy renders the approach too expensive and time-consuming except where such a model may be employed on a long-term, highly active basis. This type of activity is seen to possibly occur in the airframe industry where a baseline propulsion concept (such as a mixed flow turbofan) is often used as a reference or starting point in many advanced airframe investigations. In the propulsion industry, propulsion models are continually being updated and refined which would quickly make any regression model of a specific concept of little value.

However, it should not be concluded that regression modeling procedures cannot be used to reduce propulsion data generation costs. Many areas related to regression modeling have recently been studied under contract and have shown significant cost reduction payoffs (see References 3 through 5). In addition, the approach outlined in this report could be applied to a single engine design rather than a matrix of designs. This type of approach should provide a compact regression model which could be coupled directly to the mission assessment program, thus eliminating the need for propulsion data tables.

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